Orogenic decay from collision to rifting – characteristics and implications of delamination illustrated by a case study of the East African-Antarctic Orogen in NE Mozambique

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Dissertation for the degree of Philosophiae Doctor (PhD)

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March 2011

[“Doubt is not a pleasant condition, but certainty is absurd”]

– Voltaire

Preface

Scientific results are laid out in six contributions of research paper format. Research has been conducted in a Norwegian Research Council (NFR) funded project under the basic *FRINAT* program, granted to the principal supervisor, Prof. Dr. Joachim Jacobs at the University of Bergen (UoB). The second supervisor, Prof. Dr. Jan Kŏsler, and the candidate have also been based at UoB. Project co-operation involved Dr. Robert Thomas, British Geological Survey (BGS), Dr. Ane Engvik and Dr. Bernard Bingen, Norwegian Geological Survey (NGU). Additional analyses have been performed in external co-operation with Dr. Fred Jourdan, Curtin University, Perth, and Dr. Matt Horstwood (BGS). Scientific data and rock material from a recent mapping program were available through a Memorandum of Understanding between UoB and the Government of Mozambique. Field work was conducted in co-operation with the Geological Survey of Mozambique (DNG), Dr. Jodie Miller, University of Stellenbosch, and Dr. Christie Rowe, University of Cape Town. Additional numerical modelling was conducted in co-operation with PD Dr. Taras Gerya (ETH Zürich).

Numerous people, from within and outside research, have contributed to this work. Instead of a futile attempt to list all, standing for all those figuring above, I would like to express my deep respect and thankfulness for the support (across four continents and all times of day) and trust that I have received from both my supervisors, but especially from Joachim Jacobs. This has paved the way to candidacy for a true degree of *philosophiae* doctor which has not always appeared straight, and whose turns have not always been obvious. I am grateful to my colleagues during this time, particularly to Benjamin Emmel who has been a valuable colleague in our fortified ivory tower, Bob Thomas who naturally tided up manuscripts, Rogerio Matola who accompanied us in the field, and a vast number of geologists, officials, helpers, and nameless but mindful citizens of Mozambique.

What has been added to research and researcher, has been reduced elsewhere. The loyalty and understanding which I have irrespectively received during this time, from many people that seem too precious to appear on a formalised script, is both admirable and ashaming.

Hoping that the presented results and hypotheses will serve as a valuable starting point, the wish however is, that in the future, they will be found outdated and will be superseded by the efforts and skills of Mozambican scientists.

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Chapter 1

Introduction

The present thesis summarises work that has been carried out within a more comprehensive research project ("DELAM") which investigated the possible delamination of an orogenic root and the long-term plate margin evolution in northern Mozambique. It involves investigations on the microscopic scale and on the small scale, but widens to a local, a regional and a principal perspective. Here, an area in northern Mozambique is examined as a case study of a plate margin in order to gain insights into the development of southern Gondwana from the late Proterozoic (Ediacaran) to the late Cretaceous, and in order to make inferences on basic characteristics of decaying orogens. Observations made in northern Mozambique illustrate the mechanisms of orogenic and continental decay, but these may operate variably in different settings and might appear differently in other cases.

One field season in 2008 in northern Mozambique served to investigate key structures and to collect samples for further analyses. These studies were based on observations that supervisors and co-workers Joachim Jacobs and Robert Thomas had made in previous years during a remapping of Mozambique, taking place under the auspices of a World Bank / Nordic Development Fund funded program, being led by the government of Mozambique, and conducted by the geological surveys of Mozambique, South Africa, Norway, Great Britain, and Finland. Samples from this previous campaign were available through the Memorandum of Understanding and were complemented by samples specifically collected during own field work. Geochronological analyses have provided the insightful experience to work with numerous experts and laboratories around the world. Close collaboration with other scientists, working on the same material from another perspective, has shown the beneficial aspects of a larger research project. In addition, a spontaneously renewed co-operation with former teacher and co-author Taras Gerya, based on a common interest in principal geodynamical experiments, led to an ultimate body of results which allows a possibly unique comparison of purposive field studies, comprehensive geochronological analyses, and sophisticated numerical studies of a deep and elusive process. The results have accordingly both a regional and a theoretical scope. Acknowledging the complexity of the case, and the multitude of perspectives, the distinction shall be made clear.

1.1 Background

1.1.1 The back side of the Wilson cycle - orogenic collapse, and transition to rifting

Breathtaking heights, ferocious waters, and vast rock faces decorating mountain chains have impressed and inspired Romantic artists, mountaineers, and finally geologists since centuries. Thickened crust and topography, under attack by surface processes and erosional thinning, and the surface exposure of high grades of deformation and metamorphism allowed direct studies which promoted the development of geological sciences. Of lesser impression have been the coastlines, separated by rifting, but successfully puzzled together to unravel the existence of drifting continental masses. The seminal work of Wilson (1966) later knew to relate mountains and oceans; from instability of oceanic plates, their subsidence beneath each other, subduction, and the collision of adjacent continental masses, the eponymous Wilson cycle (e.g., Dewey and Burke, 1974) accounted for the observation that orogens took the place and even incorporated remnants of earlier oceans.

There is wide evidence that the opposite is also true; many passive margins follow the course of former orogenic systems. The complete and closed cycle at continental margins thus re-cycles through the consumption and closure of oceans, the collision and construction of elevated orogens, their cease and gravitational collapse, a coining and conditioning of the post-orogenic lithosphere, and break-up, rifting and construction of new oceans.

In comparison, of all stages, the time from collapse to break-up are the least spectacular by current geological example and the hardest to grasp. Some recent high-standing orogens record regional extension contemporaneous with convergence; ancient orogens that border an ocean, like the Norwegian Caledonides, although long broken up and rifted, can retain a considerable topographic remainder. The meta-stability of an orogen presents itself not only to be a heritage of the collision, but also to depend on the operation of un-thickening processes. A necessary refinement of reflection has to account for a number of contributing factors. These include

1. Synchronicity and diachronicity of lateral and vertical deformation, and thus different stress states, gravitational potential and lithostatic support (or boundary conditions) across an orogen. Assuming a "sequence" of "events" is a considerable simplification;

2. Modes, rates and equilibrium states of collision that characterise different orogens. Different orogens probably decay differently;

3. Differences in modes, active processes, and time scales in which the excess of crustal thickness is finally dissipated.

Thickness variations of crust (and lithospheric mantle) lead to an adjustment between excessive and deficient material. The adjustment is usually driven by body forces, by the differences in gravitational potential that are mainly differences in topography, but also in distribution of lighter and heavier rocks. Flow may be true ductile creep of low-viscosity, partially molten rocks in the lower crust of an orogen, possibly emerging as a channel. In a wider sense, the movement of material, even if brittle in shallower crustal levels and localised e.g. along extensional detachments, will describe overall (then plastic) flow from gravitational (topographic) high to low.

Unfortunately, flow and local extension are not diagnostic of the maturation of an orogenic system or the discontinuation of the underlying convergence and can occur during different stages. In a continuously growing orogen, the accommodation of lateral crustal addition by adding topography is limited; if additional height cannot be supported, the thickened domain grows by lateral flow, widening the orogen. In locking orogens where convergence ceases, flow may lead to horizontal stretching and vertical thinning in the topographical core of an orogen, while the redistribution may thicken peripheral areas (thin-skinned tectonics in the forelands). Active convergence can also be accommodated horizontally. Lateral tectonics can induce intra-plate extension and rifting ("impactogen" - e.g., Rhine Valley, Syrian-Turkish foreland) in front of an orogen (Şengör, 1976; Illies and Greiner, 1978; Hancock and Bevan, 1987; Cloetingh et al., 2005). Syn-convergent horizontal material redistribution can also be seen in indentor-escape tectonics at the longitudinal margins of an orogen (e.g., eastern central Asia, Himalaya), linking convergence (indentation) to lateral flow (escape) away from the indentor (e.g., Tapponier and Molnar, 1976; Tapponier et al., 1982; Seyferth and Henk, 2004). Here, accommodation of flow by large transcurrent discontinuities is a common feature (e.g, Red River shear zone - Leloup et al., 1995; Searle, 2006; Anczkiewicz et al., 2007).

On the large scale, plate boundaries are not necessarily limited to a narrow orogenic zone where all convergence is assimilated. Oceanic domains may include plateaus or island arcs which are accreted to the overriding continental plate before the main continental collision takes place. Oblique closures not only lead to a shifting, diachronous record of collision, but may also influences the geometry of the belt. In addition, many trenches and orogens are curved (Mahadevan et al., 2010), including arcuate deviations over 90 degrees (e.g., Apennines, Carpathians flanking the Alps in the Mediterranean region). In a wide mobile belt, curved trenches, strike-slip systems, and extending domains may coexist and interact during the same overall convergence of two principal plates as for example inferred for micro-plate fragmentation and rotational convergence of the African and European plates along the Mediterranean region (e.g., Faccena and Becker, 2010).

Various, partly overlapping classification schemes for collisional orogens exist. They may discriminate by subduction angle, by initial accretion, sediment ingestion, by orogen width, by asymmetry and vergence, by (limited) duplication of lithospheric layering, or underthrusting (e.g., Molnar, 1984), by thermal state (e.g., Chardon et al., 2009), and presumably by climatic environment. Many of these characteristics are related. For example, shallow subduction is thought to favour lithospheric doubling, and to lead to wide plateaus. Wide orogens are more likely to have reached critical thickening, therefore to have grown transversally, and to host a more extensive lower crustal domain which has undergone partial melting. Such properties certainly strongly pre-determine the unthickening behaviour of an orogen, and moreover their behaviour during break-up. Thermal state, and differences therein, control rheology (e.g., Vanderhaeghe and Teyssier, 2001). Previously developed weak zones and anisotropies (mechanical state) are likely to both lower bulk strengths and to localise deformation. This is exemplified by extension along the reactivated sole thrust and back-sliding of nappes in the Norwegian Caledonides (Fossen and Rykkelid, 1992).

Compensation and unthickening of an orogen can be achieved solely, predominantly, or jointly, by lateral escape, transversal extension, mechanical thinning, delamination, and erosion. The notion behind the different terms as used in this thesis is outlined below.

1.1.2 Destructive orogenic processes

Many processes that lead to the thinning of previously thickened crust counteract and are driven by the thickened state itself. They redistribute vertical mass away from its maxima and towards minima of gravitational potential. Their kinematic style and localisation may differ. In addition to these processes that act on their cause, some processes are controlled on other vertical levels than the crust, as for example in the lithospheric mantle or on the surface, but only operate efficiently in specific conditions set by an orogeny. The commonly practised distinction in categories as syn-orogenic and post-orogenic is, although practical, often ambiguous.

Gravitational collapse is the general non-erosional decay of elevated orogenic topography (Dewey, 1988) driven by body forces. It becomes important with ceasing convergence and changing stress states in which the lateral support for the topography as major resisting factor is no longer given. With reference to convergence, collapse is therefore often regarded as late- to post-orogenic (cf., Selverstone, 2005). There are sub-modes of collapse, depending on the boundary conditions (Rey et al., 2001). In free-boundary collapse, the adjacent lithosphere gives way readily, and allows balancing extension of the orogen without the excess potential of collapsing crust being transferred to the forelands; in contrast, collapse against fixed boundaries leads to mass and potential energy transfer to the periphery (e.g., thin-skinned thrusting).

Lateral escape is a unidirectional redistribution process dominated by far-field stresses. Characteristic for lateral escape are crustal-scale strike-slip faults along which wedges of crust are extruded transversally to the convergence direction and away from the core of an indentation zone. Escape occurs synchronously with convergence, depends on the convergent forcing, and is limited by the rheological strength of escaping material. Excessive gravitational potential can likely also be reduced after collision by an established escape regime. There are several examples of lateral escape as consequence of indentation, including Eastern Asia (e.g., Tapponier and Molnar, 1976) or the Superior Province (Canada)(Gibb, 1983). For the past, Jacobs and Thomas (2004) have also suggested a similar tectonic regime at the southern termination of the East African-Antarctic Orogen of Gondwana.

Mechanical thinning is used to describe the non-erosional reduction of crustal thickness, without dependence on high-standing topography, for example also due to far-field divergent deviatoric stresses and consequent crustal thinning. It overlaps with collapse and escape and is equivalent to tectonic denudation. Localisation of extensional flow can lead to the formation of detachments and extensional folds, depending on the boundary conditions, rheological state, and strain rate (e.g., Mancktelow and Pavlis, 2004).

Erosional thinning in contrast is thinning by surface processes which remove topography but are independent of stresses and gravitational potential. It is dependent on elevation, slope, curvature or incision of the topography, on the resistivity of rocks, and on climatic conditions that control precipitation as well as chemical and physical weathering. Both erosion and gravitational collapse compete; increasing crustal thickness, density and decreasing viscosity favour the latter (Jadamec et al., 2007).

Delamination describes a planar, (sub-) horizontal separation of the lithosphere into an upper and lower part. With regard to the common removal of lithospheric mantle and common geological effects, it is occasionally but improperly used in a wider sense to describe **convective thinning** (Houseman et al., 1981; Spohn and Schubert, 1982; Houseman and Molnar, 1997; Rey, 2001). However, the latter does not coherently separate the lithosphere along a weak layer, resembles a viscous drop (Rayleigh-Taylor instability) of lithospheric mantle, and can sufficiently be described by convection of the mantle - mantle system (lithospheric/sub-lithospheric). **Slab break-off** is a further process which results in unloading of upper lithosphere and potential opening of an asthenospheric window (e.g., Sacks and Secor, 1990; Gerya et al., 2004; Baumann et al., 2010; Duretz et al., in press). In view of the use of delamination in material

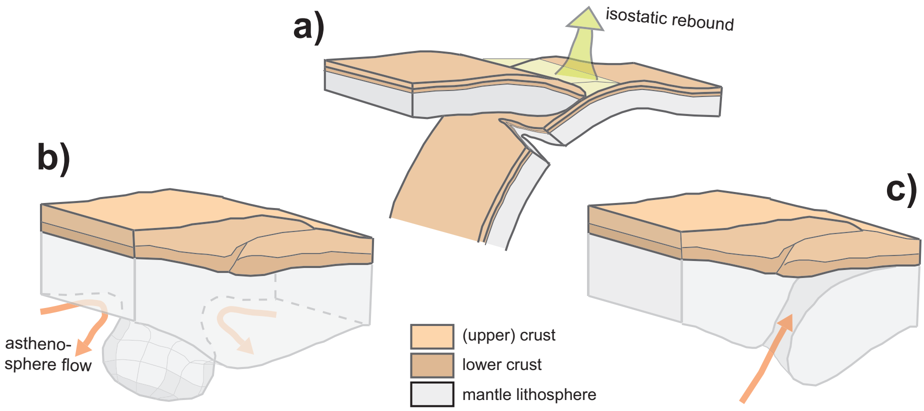

Fig. 1. Modes of basal lithospheric removal. a) Slab break-off. b) Convective thinning. c) Delamination.

science (e.g., Evans and Hutchinson, 1984; Nishikawa et al., 2007), I advocate the distinction of these terms. They might appear similar in their surface effects, but their sensitivity to orogeny likely differs fundamentally.

In contrast to other processes that might operate to the effect of mass redistribution and that thin an orogen, delamination is not driven by topographic load and differences in crustal gravitational potential itself. Most lithospheric mantle is inherently denser than the underlying, thermally expanded asthenosphere and negatively buoyant. The joint between crust and lithospheric mantle is therefore only meta-stable; it is a plane of buoyancy contrast. In an orogen, thickening or stacking of the mantle lithosphere slices can occur (Molnar, 1984) and increase negative net buoyancy. Deeper depression of the lithosphere under the orogenic root may lead to de-hydration reactions and densifying phase changes of lower gabbroic crust to eclogite, vertically expanding the negatively buoyant layer and potentially shifting the joint towards a rheological strength minimum (Ahrens and Schubert, 1975). Increased negative buoyancy, lateral differential stresses and strain, e.g. bending of the layered lithosphere, shear heating, and thus thermal and mechanical weakening of the layering, are a number of destabilising factors which account for the inferred occurrence of delamination in orogenic domains (e.g., Brown and Phillips, 2000; Schott et al., 2000). Delamination occurs where rheological strength is reduced, and likely across a buoyancy contrast (e.g., Meissner and Mooney, 1998). Accordingly, delamination could take place at different levels in the lithosphere (while convective thinning invariably is a separation within the lithospheric mantle). Although the possibility exists, it is poorly studied whether the level of delamination could laterally vary along a lithosphere section.

Delamination changes the dynamic balance of a lithosphere, but also its thermal state. The consequences of delamination are manyfold and, depending on their nature, differently distributed in time. Vertical, isostatic balancing of the new crust-asthenosphere column is comparatively rapid (e.g., Gögus and Pysklywec, 2008); the unbalanced, excess gravitational potential of the remaining crust drives extension of the delaminated lithosphere (Rey, 2001). The established geothermal gradient is disturbed as the thermal boundary layer is removed, and asthenosphere is placed in direct or close contact with crust. This amounts to a steady increase in crust heat flow until thermal relaxation is achieved. The heat anomaly decays over a geologically relevant time, until cooling of the asthenosphere replenishes lithospheric mantle. As it is put in contact with asthenosphere, the lower crust is heated above its solidus and may create high-temperature melts which can advect heat into higher crustal levels.

Geological indicators of delamination are available for surface observation but are not necessary unique. Extensive exposure of intrusions, especially those recording high temperatures (i.e., non-minimum and anhydrous melts), can be indicative of delamination, but also of other deep-rooted sources like convective thinning or mantle plumes. Rapid uplift produces topography, but is masked in thermally sensitive chronology by a changing thermal field, and might be similar to signals from other lithosphere removal processes. Uplifted and faulted topography on the surface is likely changing under extension, consequently feeding and starving limited basins of immature and proximal sediments. Increased heat flow leads to later and slower cooling of selected crustal levels in comparison to an undelaminated domain if probed by chronological methods. The differences between delamination and convective thinning are apparent; while convective thinning is ideally symmetric, delamination of layers is pinned to a moving propagation tip (singularity), is therefore highly asymmetric, and should consequently be laterally diachronous (Bird, 1979; Bird and Baumgartner, 1981).

A worldwide comparison of orogens has opened the question why some orogens apparently delaminate and some not. Leech (2001) has suggested that the occurrence of delamination is strongly dependent on the presence of hydrated rocks in subduction zones which allow eclogitisation and density increase. Eclogitisation is possibly favoured by steeper subduction. While the proposal is intriguing, a major draw-back for case studies is the frequent retrograde metamorphic obliteration of eclogite-facies assemblages. In addition, comparing the relative proportions and theoretically needed amount of negatively buoyant lithospheric mantle and of potentially eclogitisised lower crust, the dynamic relevance of the process may be limited (Schott and Schmeling, 1998). Eclogitisation could however facilitate localisation, since the rheological strength is reduced during phase change and recrystallisation and might thus provide a weak delamination horizon.

These considerations open a number of questions in understanding the extensional transition from an orogen to a passive margin and require process knowledge and attention in every case study of a transforming plate margin. Knowledge about the orogeny, from its early stages, is necessary to understand maturation and unmaking of an orogen. Knowledge about the unmaking and its lithospheric inheritance is important for understanding break-up and rifting.

Given the temporal and spatial overlap that processes at plate margin systems exhibit, it is beneficial to estimate their range in time and space, the sensitivity of these variations to initial characteristics of the system, and to estimate under which conditions these processes might start. Spatial and temporal estimates can be derived from case-studies; sensitivities have to be predicted after reduction to a sufficient model.

1.1.3 Mantle and crustal tectonics

The coupling of crust and lithospheric mantle in terms of dynamics and heat exchange imposes a dependency of crustal tectonics on deep processes even if the convective behaviour of the mantle is not considered (e.g., Melbourne and Helmberger, 2001). The mantle portion which outnumbers the crust in thickness by a multiple, depending on the age, is considered to host a major part of the rheological strength of the lithosphere, but also determines its buoyancy state. Should either its thickness or its rheological state vary laterally, then differences in crustal tectonics are a likely consequence (e.g., Corti and Manetti, 2006). A strained lithospheric mantle may develop an anisotropy that predetermines later deformation, rifting (a)symmetry and localisation (e.g., Vissers et al., 1995; Tommasi et al., 2009). Thermally, the boundary layer lithosphere-asthenosphere reflects the transition from convection to conduction (e.g., Parsons and McKenzie, 1978). Changes to the layering therefore not only change directly the ambient temperature, but the entire mode and rates at which heat is exchanged. Moreover, mantle rocks are able to store variable amounts of volatiles. In the earlier phases of convergence, release of volatiles over subducting slabs may enrich (hydrate) large portions of overlying, "wedged" mantle, in turn changing its thermodynamic and thus inherently its rheological properties during subsequent tectonics.

Illustratively, delamination is a case where crustal tectonics are strongly dependent and driven by upper mantle tectonics. Feedback is not only mechanical, but also thermal, and thermodynamical (phase changes and partial melting). Conversely, the disturbance of lithospheric layering will lead to long-term differences between an undelaminated and a recovering lithosphere. The differences are thought to be able to facilitate break-up and rifting (Rey, 2001), representing a shallower mode of thermally-activated rifting where tectonics are controlled by the lithosphere.

Most model investigations (analogue and numerical) on the lithosphere-scale are performed in boxes that account for some hundred(s) of kilometres of upper mantle. They show convective flow in the mantle, aligning with plates, and feeding back on the lithosphere (e.g., Guillaume et al., in press). On this scale, the combined lithosphere - upper mantle exhibit convection inertia, for example the stabilisation of subduction zones by mantle traction forces even after slab break-off (e.g., Conrad and Lithgow-Bertelloni, 2002). Faccena and Becker (2010) reproduced the tectonics of the Africa-Europe boundary zone in terms of a wide mobile lithosphere-upper mantle system, demonstrating the importance and complex feedback of flow and flow inertia at the scale of the Mediterranean. The consideration of mantle is accordingly a scale-dependent requirement for studies. While projections should not be undertaken on a scale of few kilometres, the continental evolution over several hundreds of kilometres is almost certainly not properly treated if the depth of perspective is not adequately upscaled. In light of the past controversies and of recent trends, it could be argued that there is no such thing as isolated crustal tectonics.

1.1.4 General questions

For the principal understanding of orogenic decay, and of individual processes that take part in the transformation of some orogenic belts to passive margins, fundamental contributions have been made earlier, while knowledge about their specifics and conjunct interplay is still in the process of development. A cautious comparison of theoretical predictions and interpreted geological cases may promote the synthesis and highlight necessary conceptual adjustments. Selected problems include:

- What are the scales of continental margin transformations?
- What are the conditions, dynamics, and time-scales for delamination?
- What is the relationships of delamination to other processes in orogens?
- How does delamination affect subsequent tectonics?
- Which constraints can geologically be derived for inherited controls on rifting?

The first general objective is to trace the tectonic development of a case-study, and when found applicable, to derive estimates for time scales, conditions, and geological consequences of delamination or other destructive orogenic processes. The second, independent objective is to principally explore circumstances and development trajectories of delamination in orogens in controlled experiments.

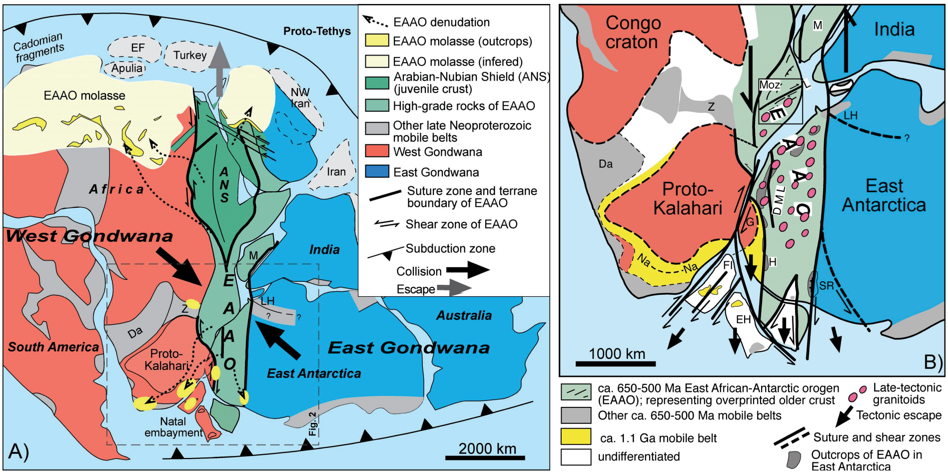

Fig. 2. Reconstruction and main constituents of Gondwana at ca. 550 Ma, with a dominant, N-S striking orogenic system, the East African-Antarctic Orogen (EAAO). Abbreviations: ANS-Arabian-Nubian shield; Da-Damara belt; EF-European fragments; LH-Lützow-Holm Bay; M-Madagascar; Z-Zambesi belt. b) Close-up on southern Gondwana and southern Africa. An indenter-escape–model is shown. C-Coats Land; DML-Dronning Maud Land; EF-European fragments; EH-Ellsworth-Haag; F-Filchner block; FI-Falkland Islands; G-Grunehogna; H-Heimefrontfjella; K-Kirwanveggen; Na-Na-Namaqua-Natal; SR-Shackleton Range; ANS-Arabian-Nubian shield; Da-Damara belt; LH-Lützow-Holm Bay; M-Madagascar; Z-Zambesi belt. Reprinted from Jacobs and Thomas (2004). [1]

1.2 NE Mozambique as a case-study

1.2.1 Amalgamation of almost a supercontinent - Gondwana

During the late Neoproterozoic to early Palaeozoic period, several present-day continents, Africa, South America, India, Antarctica, and Australia, were part of a large consolidated continental mass that mainly lay on the southern hemisphere, Gondwana (-land) (Du Toit, 1937). The continent was transected by a network of high-grade metamorphic belts with largely synchronous ages (Fig. 2), giving rise to the concept of broadly simultaneous and related Pan-Gondwanan activity across the continent.

The observation of radiometric ages of around 500 Ma in large parts of Africa first led Kennedy (1964) to conclude that they were all reflecting one "Pan-African" phenomenon. Kennedy (1964) interpreted these records as an intracratonic tectono-thermal "event", in which a homogeneous craton was subdivided along the mobilised belts into smaller cratonic cells, avoiding the notion of orogeny or collision of earlier fragments. Subsequently, this concept was modified in three ways.

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[1] Re-published in accordance with fair use principles of GSA

(1) In time, the "Pan-African" was extended and generalised to include records of ca. 800 - 450 Ma (e.g., Shackleton, 1976; Kröner, 1984; Pinna et al., 1993) or sometimes more, with the effect that more occurrences were included, but also that the temporal congruence between individual belts was reduced. Used in such a way, the Pan-African "event" lasted for up to 500 Ma which is longer than the recent persistence time of the oldest oceanic crust, as long as the presence of vertebrates on Earth, and much longer than Gondwana existed once assembled.

(2) In space, the discovery of similarly timed metamorphism in other descendants of Gondwana led to an amendment of the concept, and in order to make distinctions by region, to the introduction of equivalent terms e.g. for belts in South America ("Brasiliano"), Antarctica ("Beardmore" or "Prydz-Denman-Darling"), and Australia ("Pinjarra"), however, with variations in terminology and with respective correlations. These belts were likely continuous along and across present-day continents.

(3) The modifications were most severe and tartly debated concerning the geodynamic interpretation (e.g., "hallucinosutures": Shackleton, 1976). In defence of the thermal or intracratonic paradigm for metamorphic belts, the apparent absence of sutures and ophiolites were taken as sufficient evidence for purely thermal events, and mechanisms as plume-induced crustal thinning or intracrustal subduction were (hesitantly) proposed to allow for intermittent opening and closure of very limited oceanic basins (e.g., Kröner, 1980). The gradual recognition of eclogites, ophiolites (though incomplete sequences), and of crustal thickening; palaeomagnetic studies (e.g., Smith and Hallam, 1970; McWilliams, 1981; Meert et al., 1995; Torsvik et al., 2008); and the correlation of increasingly numerous chronological data (e.g., Hanson, 2003) from different crustal blocks shifted views towards uniformitarian plate tectonics as the origin of Pan-Gondwanan, late Neoproterozoic orogens. Accordingly, predecessor continents and terranes had to exist which collided or were accreted to form Gondwana during the (late) Neoproterozoic.

The three points above outline why "Pan-African" is a poor term. It is incapable of describing the timing in any more detail than the entire formation of Gondwana, covering the gradual change from overall divergent plate movements, over episodic additions and intermittent ocean opening, to major continental collisions. It regionally focuses on Africa as central part of Gondwana, but association with the geometry of break-up is far less relevant than association with the geometry of predecessor continents would be (e.g., "Pan-Kalahari"; or, "Circum-Indian": Collins and Pisarevsky, 2005), or with a specific destructive margin. It likely spans the occurrence of multiple closures and collisions, but does not distinguish between individual collisions between particular, delimited blocks. Sparking confusion, no clarity exists whether a reference is spatial, or temporal.

If mentioned and not defined otherwise, "Pan-African" refers here to the time span between ca. 650 and 490 Ma but does not refer to a specific region, orogeny, or orogen within Africa. Similarly, when the term "tectono-thermal" is used, it should reflect our methodological perspective, denote thermal changes due to a tectonic process as recorded by temperature-sensitive chronology, and should not imply that processes were predominantly thermal.

The basic concept behind the Pan-African, or any Pan-Gondwanan, is more restrictive than necessary, as it could suggest that the whole protracted assembly occurred within a greater scheme (e.g., "super-continent cycle"). Without doubt, the result of the assembly was a large connected continent. It is questionable, however, whether a single subduction-collision complex was sensitive to the presence of its "siblings" (or second cousins) at its time or whether their largely independent succession eventually led to an "evolutionary" emergence of Gondwana. For the study of a specific orogenic system, it is likely more appropriate to limit the scope to its converging crustal blocks and geodynamic environment.

Turning away from a single Gondwana-wide event entails increased complexity and the need for delineations (e.g., Shackleton, 1996). Recognising that Gondwana was finally assembled from at least two precursors, East and West Gondwana (McWilliams, 1981) along the eastern side of present Africa, but more likely from more ancestorial continental blocks in close succession (Meert et al., 1995; Oliver et al., 1998; Fitzsimons, 2000; De Waele et al., 2003; Collins and Pisarevsky, 2005), introduced the need for multiple orogenies that had taken place in the network of metamorphic belts. Consequently, several combinations have been devised in which constituents were first assembled to form larger plates before the last closure in two- or three-plate configuration completed Gondwana as coherent continent, or in which gradual amalgamation of many constituents occurred during overlapping time periods (e.g., Du Toit, 1937; McWilliams, 1981; Boger et al., 2001; Boger and Miller, 2004; Collins and Pisarevsky, 2005).

Despite, and because of these complexities, the metamorphic belts and orogens across Gondwana are a highly interesting study subject. The multitude of these belts of similar age spans different metamorphic conditions and tectonic styles and may or may not have interacted. It possibly represents an opportunity to study the effect of far-field changes when a comparatively large number of convergent plate boundaries operated.

1.2.2 The East African (-Antarctic) Orogen

Along the eastern margin (present-day) of Africa, a simple, and final, major closure and collision between East and West Gondwana is inferred to account for the most prominent orogenic trend, the East African Orogen (**EAO**: Stern, 1994). The EAO seems to exhibit different styles of orogeny, namely accretion in the north in the Arabian-Nubian Shield and continent-continent collision in the central and southern parts in Tanzania and northern Mozambique. While the northern part features sutures, ophiolites, encloses eclogites, and has generally undergone greenschist-facies metamorphism, the central parts exhibit granulite-facies metamorphism but lack clear geological expressions of oceanic closure. To some extent, these differences could however be related to a deeper level of exhumation in the southern (collisional) portion, exposing previous middle to lower crust, while the northern portion would equate to original upper crustal levels.

Within the EAO, in the Arabian-Nubian Shield, accretion took place between ca. 750 and 600 Ma before final suturing at around 580 Ma (Abdelsalam et al., 2002; Johnson and Woldehaimanot, 2003). In the south, in Tanzania, granulite-facies metamorphism is dated at around 650-610 Ma (Coolen et al., 1982; Muhongo and Lenoir, 1994; Sommer et al., 2003) and has been interpreted as crustal thickening following finalised accretion and collision. Subsequent eastward migration of thickening (i.e., plateau formation) has been proposed (Stern, 1994) to cause chronological data as young as 570 Ma in Madagascar (Paquette et al., 1994), but an increasing number of chronological data of ca. 550 Ma also from Tanzania and Mozambique rather points to a likely latest Neoproterozoic final collision or nappe translation in eastern Africa (Cutten et al., 2006; Hauzenberger et al, 2007; Rossetti et al., 2008; Bingen et al., 2009). Although these age records may be bimodal (Meert, 2003), both pre- and post- 600 Ma metamorphic records seem to occur invariably in the north and the south of the EAO. For example, metamorphism as old as ca. 730 Ma has recently been reported in granulite nappes of northern Mozambique (Norconsult Consortium, 2007) in conjunction with ages of ca. 550 Ma in the gneissic basement (Bingen et al., 2009).

A continuation of the EAO further to the south has been proposed by Jacobs et al. (1998) after the discovery of ca. 580-515 Ma metamorphic ages in Dronning Maud Land, Antarctica, which have since been gradually corroborated (Jacobs et al., 1998, 2003a; Asami et al., 2005; Board et al., 2005). Recently, the full chronological bimodality characterising the northern EAO has been demonstrated there, as ca. 630 Ma chronological data have been obtained (Baba et al., 2010) in likely allochthonous, high-strain granulite-facies rocks (Ravikant et al., 2004). This substantiates a continuation of the EAO to the south as the East African-Antarctic Orogen (**EAAO**: e.g., Jacobs and Thomas, 2004).

In spite of this, a southwards continuation into Antarctica (Dronning Maud Land) has been contested, primarily on grounds of the occurrence of similar metamorphic ages both to the west and the east of Mozambique (e.g., Meert, 2003; Collins and Pisarevsky, 2005). To the west, the Damara and Zambesi belts and the Lufilian Arc between the Congo and Kalahari cratons exhibit ages of ca. 540-500 Ma (Vinyu et al., 1999; John et al., 2004; Johnson and Oliver, 2004; Johnson et al., 2005; Gray et al., 2008) that are similar to ages to the east, in northern Antarctica around Lützow Holm Bay, Prydz Bay, and the Prince Charles Mountains (e.g., Harley et al., 1998; Boger et al., 2001; Corvino et al., 2008; Liu et al., 2009). Alternative models either postulate regionally limited simultaneous collisions (e.g., Collins and Pisarevsky, 2005), or that final closure of largely pre-assembled plates took place along an E-W trending orogenic belt continuous from present-day west Africa over Antarctica to Australia, termed "Kuunga" orogen (Meert, 2003; cf. Bingen et al., 2009). The two proposals for large continuous belts, apparently cross-cutting each other (EAAO : N-S; Kuunga: E-W), conflict, as either implies closure between the two separated sides of each, thus requiring that the other was discontinuous if not four plates collided simultaneously.

In the EAAO, not only the style of orogeny varies, but also the operation of destructive orogenic processes (*cf. section 1.1.2*). Escape tectonics have been proposed at both ends, in the north in the Arabian-Nubian shield (Stern, 1994, and references therein) and in the south, where divergence of microplates along strike-slip systems probably represents lateral escape at the southern termination of the EAAO (Fig. 2b; Jacobs and Thomas, 2004). Comparatively little is known about (gravitational) orogenic collapse. In Tanzania, collapse is inferred to be of minor importance based on slow cooling rates within granulites (Möller et al., 2000). In Madagascar, collapse is recorded along some extensional detachments (e.g., Collins et al., 2000), associated with elevated temperatures, post-collisional granites, and charnockitisation between 530 and 490 Ma (de Wit et al., 2001; Goodenough et al., 2010). In Antarctica (Dronning Maud Land), ca. 530 - 510 Ma extensional shear-zones coincide with partial melting and the emplacement of large volumes of granitoids (Bauer et al., 2003; Jacobs et al., 2003b, 2008; Engvik and Elvevold, 2004), similar to the then adjacent parts of Mozambique, and possibly reflecting lithospheric delamination (Jacobs et al., 2008). The lack of sediments sourced from the EAAO in most foreland regions have so far made it difficult to constrain erosion, sedimentation, and palaeoenvironments, and to estimate the relative importance of erosional thinning.

After incorporation into Pangaea, extension and thinning continued or commenced during the Permo-Triassic as reflected by intracontinental basins (Karoo), and culminated in the Jurassic to Cretaceous break-up, leading to the opening of an ocean between East African, Antarctic, and Indian fragments.

East Africa leaves a number of questions open with regard to the continuation of orogenic systems, but also with regard to retro-orogenic tectonics. The fact that the present eastern margin of Africa coincides well with the location of major orogenic remnants indicates significant tectonic inheritance, but this again highlights the limitation of knowledge about collapse and extension.

Fig. 3. Characteristic exposures in NE Mozambique. a) Smooth inselberg exposures, here of meta-sedimentary rocks (Mecubúri Group). Inselbergs occur in a variety of lithologies. b) Rough and isolated exposures of granitoids are characteristic. Here, the Lalaula pluton is shown, intruded into the Lúrio Belt. c) Poor exposure in the eastern part of the Lúrio Belt.

1.2.3 NE Mozambique in East Africa

The region of NE Mozambique is promising for the study and characterisation of post-collisional plate margin development because it comprises a part of the orogen where the occurrence of fast orogenic deconstruction has been substantiated, and an adjacent, contrasting part that has decayed more gradually. Two passive margins that fringe the area follow the orogen in different styles and may relate to differences in orogenic evolution. In addition, the region is of interest because it is situated within Gondwana where the first-order N-S (EAAO) and E-W (Kuunga) orogen system trends intersect.

Deep exhumation levels in NE Mozambique expose middle crust and represent an opportunity to study the deep crustal expressions of collision and especially collapse in the EAAO. At the same time, the deep exposure level diminishes the possibility to observe and identify characteristic upper crustal expressions of some geological settings, such as ophiolite sequences or sharply localised extensional detachments. The field area studied here is bounded to the west by Lake Malawi, to the north by the political border to Tanzania, and along the eastern and southern sides by the coast line of Mozambique as far as ca. the town of Quelimane. The landscape exhibits in general low and smooth hilly undulations (Fig. 3c), and rises little from the eastern coast at around 0-250 m to 500-750 m to the west. Significantly higher elevations of over 1250 m occur only on the rift shoulder of the East African Rift in the northwest. Field exposure in NE Mozambique is variable but generally scarce. Characteristic inselberg exposures punctually rise over the hilly landscape and are made up of vastly different rock types (Mesoproterozoic gneisses, late-tectonic granitoids, meta-sediments), but their origin is not completely understood (Fig. 3a).

Holmes (1918,1951) first recognised the high metamorphic grade and the deep exhumation levels in NE Mozambique, and consequently proposed the regional concept of a N-S trending orogenic "Mozambique Belt" that is equivalent to the central, collisional part of the EAO. In the decades following, geological studies were mostly conducted with an industrial scope and did not widely expand into published literature. After the end of the civil war, a milestone study by Pinna et al. (1993) provided a comprehensive characterisation of the geological units and their relationship in NE Mozambique applying more modern tectonic concepts. In the many years of geological research, until recently, the timing of principle orogeny reflected in the region, whether late Mesoproterozoic (ca. 1100-950 Ma - "Mozambican"; "Lurian"; "Kibarian"; "Grenvillian") or late Neoproterozoic (ca. 600-550 Ma - "Pan-African") has been debated (e.g., Pinna et al., 1993; Kröner et al., 1997; Sacchi et al., 2000). Whilst most of the early work attributed little tectonic importance to the Late Neoproterozoic to Early Palaeozoic period for shaping the crust to take its present structure, and rather followed the notion of a largely thermal overprint, the latter event gradually gained attention as a possible tectonic alternative (Pinna et al., 1993; Kröner et al. 1997). Only relatively recent studies robustly established the late Neoproterozoic / early Palaeozoic orogeny to be more strongly reflected in the structural and metamorphic record than any earlier tectonics (e.g., Norconsult Consortium, 2007; Viola et al., 2008; Bingen et al., 2009; Macey et al., 2010). It remained however unaddressed how strong the destructive orogenic processes had modified and redefined the crustal structure and fabric in NE Mozambique.

The recent (re-) mapping of NE Mozambique has led to a new tectonic and lithodemic subdivision (Norconsult Consortium, 2007; Viola et al., 2008; Boyd et al., 2010; Thomas et al., 2010). The main crust forming ages of the gneissic basement are Mesoproterozoic to Early Neoproterozoic (Bingen et al., 2009; Macey et al., 2010). The crust is laterally divided into two parts by an enigmatic and lithologically complex shear-zone. To the north of this zone, the Lúrio Belt, amphibolite-grade basements gneisses are overlain by high-strain, granulite-facies rocks that form a nappe complex (Cabo Delgado Nappe Complex, **CDNC**: Viola et al., 2008) bearing similarity to granulites in Tanzania. To the south, the equivalents of granulite-facies rocks are scarce and limited to two small klippen. The block south of the Lúrio Belt (coincident with a single extensive basement complex, the Nampula Complex) hosts large volumes of granitoids (partly with distinct high-temperature signature) which are late with respect to late Neoproterozoic collision. A few younger metamorphic U-Pb zircon ages within the basement agree in time with the emplacement of voluminous granitoids (Jacobs et al., 2008; Bingen et al., 2009; Macey et al., 2010). Rocks of granulite-facies nappe affinity, and high volumes of intrusives which are delimited by tectonic boundaries are similarly found in Dronning Maud Land in Antarctica. While collapse is evident in the southern part of the study area in Mozambique, it is insufficiently characterised and so far lacks systematic correlation with corresponding structures.

Geological situation and crustal structure of NE Mozambique have been interpreted differently and are reflected by distinct models (Fig. 4). Pinna et al. (1993) envisaged a Mesoproterozoic collision and juxtaposition of the northern and southern block along the Lúrio Belt (Fig. 4a). Nappes were transported from

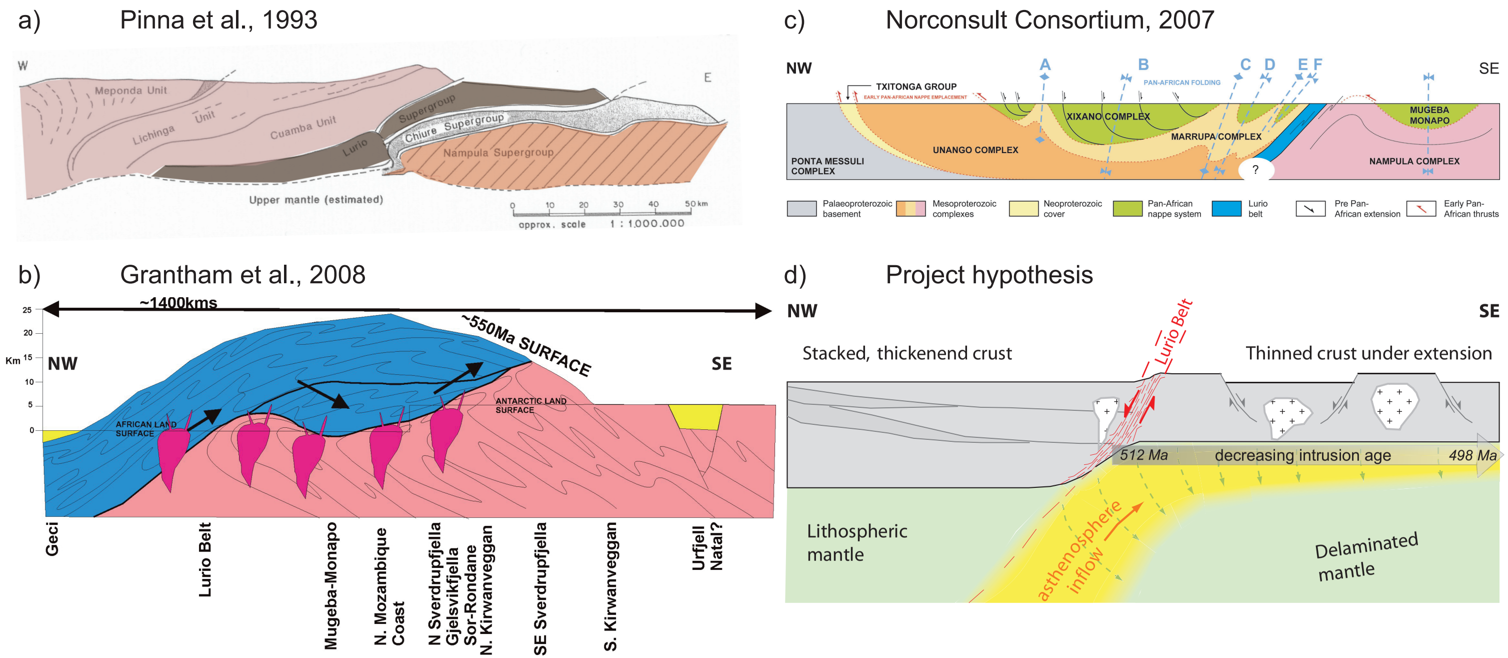

Fig. 4. Models for tectonic situation, timing of collision, and the role of the Lúrio Belt. a) Mesoproterozoic collision with flat-lying suture and southwards nappe transport after Pinna et al. (1993). With permission from Elsevier. b) Modified model with Late Neoproterozoic southwards thrusting of a mega-nappe. Republished with permission from Grantham et al. (2008). c) Model of folding and thrusting (Norconsult Consortium, 2007; also published in Viola et al., 2008). Blue lines and letters denote traces of large-scale fold axial planes. With permission from the Geological Survey of Mozambique (DNG). d) Delamination model with removal of lithospheric mantle from underneath the Nampula Complex and the subsequent formation of crustal melts.

the NW to the SE. Recognising a number of Pan-African thrusts, especially in the north of the area, they interpreted the modification of crust during this time as both thermal and tectonic, but attributed the tectonics to intracontinental deformation. Grantham et al. (2008) adopted the geometry of the orogen, but proposed late Neoproterozoic collision and thrusting of a mega-nappe southwards (Fig. 4b) which extended from Tanzania into Mozambique, Sri Lanka, and Antarctica (Dronning Maud Land and Lützow Holm Bay). Studies by the Norconsult Consortium (2007) and Viola et al. (2008) of the high-strain, granulite-facies rocks, and of structures predominantly in the Lúrio Belt and towards the north, led to the recognition of the Cabo Delgado Nappe Complex and of large scale folds with increasing strain towards the Lúrio Belt (Fig. 4c). These two studies found indications for a northeastwards directed nappe transport. These conflicting senses were avoided before by some earlier proposals of a bivergent geometry of the nappe system rooted in a collision zone along the Lúrio Belt (e.g., Jourde and Vialette, 1980), but did not benefit from the comprehensive data-set available today. Accordingly, the role of the Lúrio Belt has been seen differently in these different studies. In the model after Pinna et al. (1993), the Lúrio Belt is interpreted as a flat-lying suture zone, and similarly in Grantham et al. (2008). In the model of Viola et al. (2008), the Lúrio Belt is the basal high strain zone along which the nappes were transported, and gained its present shallowly NE-wards dipping attitude only later. Shackleton (1996) has taken the Lúrio Belt to represent a syn-convergent transpressional shear zone without the local closure of an ocean. Jacobs et al. (2008) have suggested that the Lúrio Belt be a (vertical) accommodation zone, and that the present attitude and late kinematics of the Lúrio Belt were due to normal-sense slip under extension in which the southern block was rapidly exhumed following removal of mantle lithosphere.

This was supported by the observation that voluminous granitoid intrusions sharply terminated along the Lúrio Belt. Those, and additional indications of late tectonics led to the proposal of a delamination model (Fig. 4d) which underlies this work. In this model, the delamination is partial, meaning lateral variation in whether the lithosphere has undergone delamination or not. Specifically, the southern part of the basement in NE Mozambique (and Antarctica) is taken to have undergone delamination, leading to partial crustal melting and rapid uplift, while the adjacent complexes to the north of the belt would have not. In such a case, rapid uplift in the south would have implied differential slip along the Lúrio Belt localising the differential exhumation movement. The delamination hypothesis which defined the starting point of the research project is based on the following observations:

1. Large volumes of granitoids that are apparently missing to the north of the Lúrio Belt;

2. late Neoproterozoic / early Palaeozoic migmatisation in the basement south of the belt, which ...

3. ... is closely correlated with a suite of extensional structures;

4. Different spatial extent to which the basement on both sides of the belt is overlain by rocks of nappe-affinity. The significantly smaller extent in the south might reflect deeper exhumation of the southern crust due to uplift and thinning.

If these indications are correctly interpreted, the comparison of the areas north and south of the Lúrio Belt is a comparison of undelaminated and delaminated lithosphere. This lateral change would represent a further, dramatic variation of characteristics along the Himalayan-style EAAO.

After onset of large-scale reconfigurations and break-up of Gondwana in the Permian, rifting lead to the opening of oceans, adjacent to the eastern margin fringed by the Rovuma basin in the Jurassic, and to the southern margin forming the Mozambique basin in the Cretaceous. The transition period between the decay of the EAAO and the break-up, the tectonic and cooling characteristics of the two margins, and their interaction may hold hitherto unknown implications for the orogen-passive margin transformation and its understanding.

1.2.4 Particular questions

Recent geological observations and samples cover a large area in NE Mozambique. They have opened up opportunities for large-scale studies of orogenic and post-orogenic development, and have identified a number of interesting geological questions. The following aspects of the NE Mozambique case are of particular interest:

- Are there indications whether the current tectonic disposition is the result of one or two orogenies (*Kuunga* vs. *EAAO*)?
- What are the main characteristics of the late Neoproterozoic / early Palaeozoic orogen?
- Is there stringent evidence against or corroborating evidence for delamination?
- What are the post-collisional tectonics, structures, and thermal histories in the main tectonic units?
- How did the Lúrio Belt develop and evolve? Can differential exhumation, and thus normal kinematics, be inferred?
- What are the characteristics, thermal histories, and geometries of the passive margins?
- Did orogenic and retro-orogenic processes influence break-up and rifting?

The objective in the case study is to characterise the plate margin from its convergent to divergent phase, to identify and compare collisional and possible post-collisional structures, and to obtain and compare combined cooling data for the retrograde evolution of different crustal levels. Ultimately, an eclectic and robust data-set should be obtained that decisively tests the delamination hypothesis.

1.3 Research approach and Methodology

Every general methodology comes with a number of challenges and involves a trade-off between the benefit to extract an understandable result and the cost of limited validity (non-universal applicability) of this result. The choice of particular methods for a study depends ideally not only on the availability of the tools, or their non-availability (e.g., seismic receiver function studies to map the lithosphere-asthenosphere boundary), but the understanding and mastering of the challenges that characterise their suitability. The characteristics of an approach that require attention may be described in a set of terms as for example outlined below.

Reduction of the problem and introduction of assumptions. Only the reduction to a number of considered factors make analytical treatment possible. Apart from theoretical calculations, it is for example common that a certain exposure area or block is considered to be geologically homogeneous and to have undergone the same deformation, metamorphism and cooling. A vertical lithosphere section is considered to consist of homogeneous layers in which changes of intensive properties can be described in simple terms. However, the assumptions may restrict the applicability of the model to special cases, and limit the significance of predictions beyond.

Resolution and data scarcity. Direct measurements have an uncertainty (see below), a quantitative scale below which a measurement cannot be reproduced. Since finer distinctions do not have any significant meaning, the knowledge of this scale, or resolution, is crucial. For example, optical microscopy is limited to about 0.2 μm; (academically available) satellite imagery has a resolution in the dm-scale, but in these cases, the resolution is easily recognisable. Underlying these optical cases, wave-form data (also: time series; seismic waves) do not resolve an information component that is "spaced" or "sized" to less than twice the sampling scale (reciprocal of *Nyquist frequency*), a concept that should similarly apply for interpolation. Indeed, data acquisition in geology is mostly punctual. Limited capacities and resources often lead to scarce sampling, e.g. of structural readings and even more so of hand-pieces for laboratory analyses. Spatial coverage is often contingent on geological exposure conditions and accessibility, or on the occurrence of material suitable for analyses in collected samples. As a result, coverage is potentially uneven. Scarcity is not limited to space, but may amongst others include limitations in time, temperature, and pressure information. Scarcity and uneven distribution determine the respective resolution. In inversion theory, problems can be classified as underdetermined, overdetermined, or mixed-determined, depending on the coverage of information to be gained (model space) by observations (data space). It is apparent that resolution can locally vary if a problem is mixed-determined, and mapping of the resulting resolution is then of interest. A spatial example of an indirect resolution estimate is the goodness of recovery of known, artificial velocity anomalies in seismic tomography, using the coverage (e.g., ray-tracing) of the real seismic data set.

Analytical uncertainty. Such uncertainties can for example include the uncertainty of a structural reading ($\mathcal{O}(5^\circ)$), to which a measurement could be reproduced at the same structure, or the statistical variance of an averaged (integrated) laboratory measurement. In contrast, variations in structural readings also occur when a measured plane is slightly uneven, as do variations in metamorphic age when dated samples are spread over an area. In the latter cases, additional uncertainty is superimposed on the analytical uncertainties because the reduction is flawed - the assumption that a foliation is planar, or that analyses in given rocks of different composition reflect the same conditions, is only approximate. A distinction between analytical and non-analytical uncertainties is important, since the latter potentially mask the original relationship to resolution. Estimates of resolution in any parameter require therefore a distinction of uncertainties. If properly used, uncertainties can be *a priori* incorporated in inversion schemes and mapped on *a posteriori* uncertainties.

Non-uniqueness. A single observation does not always have a single possible cause. For example, folding as a general phenomenon can both occur during crustal shortening and during extension. A continuous increase in recorded temperature (or metamorphic grade) along a geological traverse can either indicate proceeding into an orogen, moving towards a large magmatic body, or simply the surface exposure of different vertical levels (e.g., due to block tilting). In theoretical treatment, an inverse calculation may yield different results depending on an initial guess if the probability measure has more than one maximum in model space.

These trade-offs and limitations are inevitable, but not a fate to which one has to resign oneself. Instead, their effect should be assessed as far as possible. In theoretical analysis, the variance of a solution can often be obtained analytically; in other cases, it is sufficient to alter the variables that are fed into a calculation and to observe range or variance of the targeted quantity. The latter approach is a possible way to explore the effect of assumed homogeneity versus potential heterogeneity. Other, measurement-intensive methods (e.g., geochemistry and geochronology) allow to directly observe the variance of measurements, and thus provide statistical expressions of uncertainty and reproducibility. It is however challenging to assess the possible non-uniqueness of a result or even more so of an interpretation. In forward-inferring approaches, comprehensive sampling of a parameter range (space) can allow the identification and probability ranking of multiple solutions (e.g., Monte-Carlo method), thus mimicking a true inverse inference. For a particular geological observation, it might be possible to establish a limited number of interpretations which may all account for it. The assessment of the limitation is here the clear statement that these diverging interpretations exits. Combination of multiple observations may then isolate a most probable interpretation.

1.3.1 Options and strategies towards quantitative geology

If conceptual reproduction in a model is simplified enough, theoretical mathematical, geophysical, thermodynamical or geochemical predictions can be derived for the scope of the given assumptions. For example, in the case of delaminated lithosphere, it is possible to calculate the cooling half-time for sub-crustal mantle, i.e. to estimate the static transition of uppermost mantle material below a homologous temperature that represents mantle lithosphere, provided that convection and latent heat exchange can be neglected. The results predict replenishment of half of the initial thickness after ca. 60 Ma (Nelson, 1992, and references therein). It may however be doubted if adjusting mantle movements and heat exchange on such a scale occur statically. The analysis of orogenic collapse by Jadamec et al. (2007) is also an **analytical solution** where the simplification is the treatment of an orogen as a sinusoidal crustal thickness anomaly, and the representation of erosion by a general diffusion scheme. Analytical solutions have infinite resolution, are well determined, and incur no uncertainty in terms of reproducibility. However, their reduction to a handful of considered quantities involves severe simplifications and assumptions that might lower their significance.

The limitations of analytical solutions can be alleviated if calculations of the former kind are combined and discretised. Discretisation in a number of coupled spatial elements, for which properties are sequentially calculated in small discrete time steps, allow approximation of complex (e.g., inhomogeneous) cases which exhibit non-linear relationships and for which no analytical solution exists. **Numerical modelling** also allows for feedback of several changing properties, for example temperature increase during viscous deformation (shear heating), resulting partial melting, lowering of effective viscosity, and thus further localisation of deformation. In contrast to analytical solutions from which they are derived, numerical models have scale and resolution which are known. They have the great advantage that a wealth of physical parameters (p,T, X, density, velocities, stresses, strain rate, heat flow) is directly available on a grid, and can be traced through time. Scarcity is a problem when discretisation is too coarse to resolve the effect of small-scale variations. Reduction and assumptions are severe, but can, in principle, individually be eliminated if a satisfying formulation of a process is available and restrictions in resolution and computational resources can be overcome. Special assumptions exist in the form of initial and boundary conditions which are also known. Usually, models evolve almost identically, establishing a fairly unique forward link between a set of model parameters and a set of observations (final distributed properties). In comparison, **analogue modelling** is more severe in assumptions but resolution is less resource-consuming, and independent on human coding errors. Uniqueness is given. However, there are uncertainties in the observation process that relate to the assumptions of comparability. These include uncertainties in the real rheological properties of the analogue material which are used for scaling, and in the effect of boundary conditions.

Geological field observations vary in their significance. They are harder to interpret correctly and to treat quantitatively, but are principally the most immediate and significant inferences possible. Relational observations (e.g., cross-cutting relationships) are more reliable than absolute quantifications. Both have a scope of validity. A cross-cutting, unfoliated dyke in a gneiss is a unique temporal relationship with ideally no observation uncertainty, unlimited reproducibility, but a limited validity for a usually unknown spatial extent. Spatially distributed observations like geological boundaries, sedimentary facies, or metamorphic grade, quickly become scarce due to exposure, and uncertain below a given scale. Other properties like grain sizes might vary from outcrop to outcrop for one lithology, representing an inherent uncertainty. On the other hand, generalisation and simplification might incur non-uniqueness, when the natural variation is not considered, mostly, because the tools for their consideration are lacking.

The dilemma is illustrated in Fig. 5. In this example, structural measurements of geological structures are shown, as commonly practised in structural geology. It is also established practice to take a large number of measurements to increase robustness. For quantitative treatment, simple statistical measures exist. The two spatial coordinates (spherical: azimuth, dip) can be described in terms of a bivariate normal distribution, the Fisher distribution. Its parameters, or moments, give a mean orientation and a spatial variance; however, the variance is nothing more than the angular distance (scatter) around the mean, describing a circular confidence cone. This is often a poor description of real data, and natural scatter, especially outliers, can lead to undesirable and distracting estimates, as shown in Fig. 5b. This kind of statistical description has the advantage that exact confidence intervals can be calculated, and that statistical tests are available. The disadvantage is that the assumption of circular distribution is such a severe assumption that tests fail routinely on confidence levels as generous as 90%. In Fig. 5a, the Fisher estimates of two data sets are shown; their 95% confidence cones only slightly overlap, the test fails, while the data sets seem reasonably similar. In comparison, the overlain estimates for

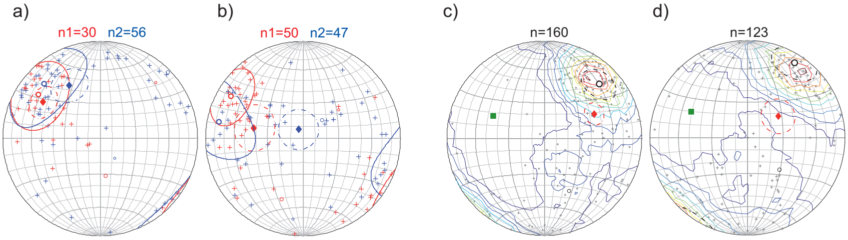

Fig. 5. Methods for comparison for oriented data (equal area, lower hemisphere projection). a,b): two sets of linear data are shown as crosses of different colour. The meta-sedimentary group is shown in red, its subjacent basement in blue. Diamonds and hatched circles: mean vector and confidence interval (95%) of fitted Fisher distributions. Open circles and solid ellipses: Bingham moment of maximum concentration direction and confidence estimate (95%). a) Lineations - Fisher estimates show less agreement than Bingham estimates. b) Fold axes - Bingham estimates overlap, while Fisher estimates do not. Apparent mismatch due to strict minimisation of distances to mean. c,d) Comparison of Fisher and Bingham distributions with probability contours (Kamb, 1959) of foliation poles from meta-sediments (c) and basement (d). Bingham estimates would again overlap and coincide with contoured probability maxima, while Fisher estimates would not. Green squares denote minimum concentration directions and correspond to fold axes. Mathematical and graphical routines implemented following Kamb (1959), Onstott (1980), Cheeney (1983) and Pollard and Fletcher (2005).

an other statistical distribution agree much better. The underlying distribution is the Bingham distribution (Bingham, 1964; Onstott, 1980; Kent, 1982,1987) which has in minimum five moments (parameters). Its parameters include directions of highest, lowest, and intermediate data concentration and measures of ellipticity that can for example describe the girdle shape reflecting folding. The distribution is implemented in many common stereographic software, where inferred fold axes are the moments with the minimum concentration, and the orthogonal maximum and intermediate directions span the girdle (Fig. 5 c,d). However, the Bingham distribution is of such mathematical complexity that the confidence ellipses are only an approximation (Cheeney, 1983), and that no rigorous statistical tests have been established. In the presented case, a meaningful testing of congruence (rejection of difference) would be crucial; it compares the data of a late-tectonic meta-sedimentary unit (the Mecubúri Group; see below) and its subjacent basement. Identity would have meant that deformation had occurred after collision in the orogen; however, the quantification was strictly speaking not successful. This example might be taken as a firm justification for the qualitative treatment practised by geologist, resorting to reasonable optical comparison (e.g., Fig. c,d) and experience.

Due to the immense complexities and inhomogeneities in nature, field observations are however the most immediate observations and are commonly used to assess the reproducibility of other methods.

In **geochronology**, the deduction process is different. Isotopic age determinations make use of the decay of radioactive elements which are enriched in suitable minerals, but do not directly translate to rock ages. They date the time when diffusion of isotopes through the lattice of a crystal becomes ineffective, and daughter isotopes are retained and start to enrich. Simple diffusion can be described in terms of an Arrhenius relationship (Dodson, 1973), according to which it is thermally activated. Thus, diffusion closure and the accumulation of isotopes to first order dates a cooling through a certain temperature. Exceptions exist when minerals grow below this closure temperature, for example due to elevated activities of one chemical component that preferably partitions into the mineral in question (e.g., excess availability of Zr or Ti), or when chemical reactions in the host rock exchange elements with portions of a grain and thus open the lattice for diffusion (e.g., Frost et al., 2002).

Although the complexity of these methods incur a number of assumptions, their effect is comparatively well studied and can be considered to be controlled. Usually employed assumptions in geological case studies include

- Complete and rapid halt (closure) of diffusion out of a grain when passing through a certain closure temperature (Dodson, 1973);
- Simultaneous closure of a non-reactive grain over its whole volume (see Cherniak, 2006);
- Simultaneous closure within one locality (or sample), taken to quantify the variability of measurements over several grains;
- Independence of diffusion closure on varying chemical composition, and thus the same closure temperature for every lithology;
- Independence of diffusion on neighbouring grains, thought to act as sinks of infinitely high diffusivity;
- Inert behaviour of minerals in chemical (metamorphic and metasomatic) reactions during changing $p-T-X$ conditions (see Frost et al., 2002);
- Absence of microscopic inclusions that are enriched in parent and daughter isotopes of the system in question;
- Homogeneous distribution of isotopes in an extended grain area, where the requirement for robust sampling (i.e., area ablated) incurs the risk of mixing both laterally and in depth;
- A simple cooling history without partial reheating to temperatures where limited diffusion starts to deplete daughter isotopes (cf. treatment by Meesters and Dunai, 2002; Gardés and Montel, 2009).

Similarly, multiple factors of uncertainty exists but can in a number of cases be treated (propagated). Uncertainties include

- Analytically, the precision of the mass spectrometer, the uncertainty of age standards used to calibrate measurements, and the statistical variance of time-integrated analysis intervals;
- In mass-spectrometry, control on effects like fractionation, instrument drift, and the calibration of tracer solutions that are used to correct for mass bias;
- The knowledge or estimation of closure temperatures, by experimental determination of kinematic parameters for a mineral, or by comparative case studies;
- The applicability of thermal closure, as opposed to growth or recrystallisation below closure temperature.

The interpretation of geochronological and thermochronological data is unfortunately non-unique. Thermal control on age qualitatively aligns them with spatial increases in temperatures, for example with increasing depth. Consequently, it is not possible to say whether age differences are a consequence of different cooling across the same vertical level, or of different exposure levels, or of different ambient temperatures and geothermal gradients. For example, increasing metamorphic grade from the periphery to the centre of an orogen may produce an age gradient similar to the exposure of different erosion levels of crust which never underwent different metamorphic conditions. Another aspect of non-uniqueness exists in temperature history; an age does not date the peak of metamorphism (in temperature), but the latest point the temperatures higher than the closure temperature prevailed. Theoretically, a peak could have occurred any time before, and the age is with a certain likelihood lagged. The most inconvenient aspect of thermally sensitive chronology is accordingly the difficulty to translate temperature information to depth information, or to establish a spatial reference while simultaneously investigating changes in the thermal field. This is a highly multivariate, non-linear problem, since in addition, the temperature at which ages are recorded (closure temperature) also depends on the rate of cooling.

Spatial correlation, or dimensionality, is established by geographical spread of samples. Since analyses pose heavy requirements on time, preparation, and operation costs, data sets are usually scarce. Assessments of resolution and propagated uncertainties should therefore be attempted wherever possible.

Despite these difficulties, timing information is invaluable for the reconstruction and comparison of tectonic evolution. Eliminating some of the variance, by external constraints, or by a well-chosen tentative assumption, may allow additional estimations of thermal and even vertical development. Such simplifications can be justified by the study of numerical models where both changing geothermal fields and vertical movements are considered in the genesis of age records. In addition, treatment of scarce data, and of thermally sensitive data, can be improved quantitatively. Three measures can be implemented to take into account external uncertainties which are in comparison to the analytical (internal) uncertainties usually rather poorly handled:

1. **Estimation of resolution.** Most geochronological and geochemical data, and to certain degree geological data, are punctual. It can be estimated how well these points resolve a real natural feature, or how unique an interpretation is. This is common practice in seismic tomography, where the coverage or illumination of the small model volumes to be predicted (voxels, as three-dimensional equivalents of pixels) by the real earthquake data sets is analysed. Calculations are performed with synthetic anomalies, and their modified recovery, or projection, on the models are observed. The adoption which can be made is to take synthetical, thus known geological scenarios with a reasonable scale and variability, and to apply exactly the procedure which is planned for the real data set. An example is given in Fig. 6 along with a corresponding interpretation mechanism (interpolation) which propagates uncertainties, allows for regularisation of mixed-determined problems, and does not interpolate on a regular grid, but rather on a number of irregular triangulation cells which better reflect the geological geometries;

2. **Combined interpretation of multiple systems.** Combination of data from different temperature ranges has several advantages. Firstly, the combination allows to estimate a cooling rate through each system, with which then the rate-sensitive closure temperature can be calculated iteratively. In addition, wholistic cooling paths allow for a quick recognition of relative contributions in time, and might alert to late modification and disturbance of deeper levels (higher temperatures) that have been passively advected. Ideally, one should start from the latest, lowest-temperature increment and subtract this effect from the higher temperatures which have accumulated all exhumation increments. This could be regarded as thermal back-stacking, but is in practice limited by the number of viable chronometers;

3. **Robust treatment of external errors**. When grouping data, the combination of mean or central values is comparatively easy while a combination of their uncertainties is rather difficult. To account for the fact that two ages have not only small internal uncertainties but their central values lie far apart (external uncertainty of their distribution), common tools only offer mean and standard deviation measures which quickly become meaningless. Instead, relative probability densities of the individual data can be summed up. These combined sets represent the probability distribution better (within assumptions inherent to the analyses) and can be taken as starting point for the combination of multiple chronometers and the construction of cooling paths.

In **thermochronology**, similar considerations hold true. Fission-track analyses are based on the density of radioactively created lattice defects, whose annealing is also thermally activated. Annealing has been well studied, and slows down over an extended temperature range (*partial annealing zone*). In contrast

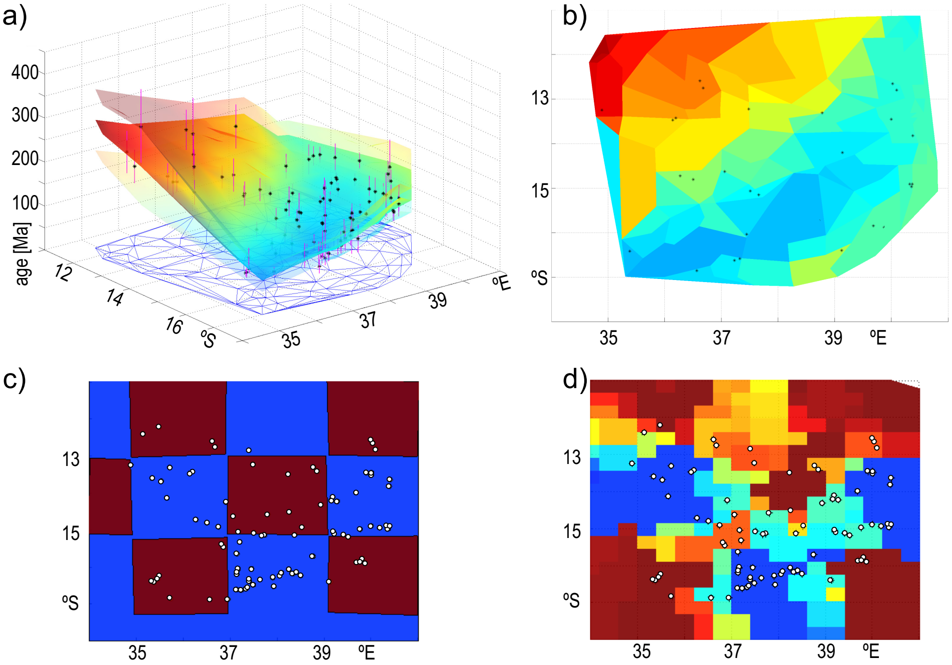

Fig. 6. Interpolation algorithm (a,b) with custom geometry, and resolution estimation (c,d). Interpolation shows individual analyses with their errorbars (a), elevation, colour = age); the interpolation is strongly regularised (a,b). For the resolution estimation, synthetic age distributions (c) are set on points at the same position as the real data and with exactly the same analytical uncertainties. They are put through the same procedure (e.g., interpolation) than later the true data values (d). Note that interpolation and resolution estimation are shown on different interpolation grids.

to other methods, additional information on the change of temperature through time can be obtained from incomplete annealing. Track length distributions represent an integrated effect of the whole time-temperature development on a population of continuously forming tracks. Distributions for given $t-T$ paths can be modelled forward using a kinematic annealing model, and can be compared to measured distributions. Random probing of paths (as the varied parameters) allows to map probabilities (Monte-Carlo approach), and thus to infer a likely thermal history for a given track length distribution.

With a combination of independent methods, the conducted research investigates large-scale, decay-related, deep-seated processes from different perspectives. It illuminates three different levels of the lithosphere. Shallow crustal levels correspond to fission-track data and low temperature; they record late history, including break-up and rifting. Mid-crustal levels are reflected in geochronological data and field observations. Finally, the systematic participation of mantle in depth in these processes is addressed by numerical modelling.

Chapter 2

Synopsis of research

The particular and general questions and the objectives of this thesis are addressed by six articles which together cover the geodynamics of delaminating orogens, aspects of the amalgamation of Gondwana, the post-collisional development of the EAAO in NE Mozambique, and the break-up and rifting history along the former orogenic margin. The first five of six individual contributions (articles) that follow as chapters are arranged in order of broadening perspective, starting from small-scale observations, tackling increasingly regional studies and finally covering the plate tectonic scale. The sixth contribution is a summary in which key findings are summarised. Also, the first four contributions constituting the case studies represent a temporal shift of focus within the EAAO from an early Cambrian syn- to post-collisional stage, over post-collisional expressions of collapse, to break-up and rifting up to the Cretaceous.

Attempts to separate and to characterise possibly multiple tectonic episodes, and thus studies of destructive processes in orogens (*cf. section 1.1.2*), rely on the availability of suitable tectonic markers which provide the necessary, unique geological relationships for an analysis. The Mecubúri Group (**Contribution I**) that overlies the gneissic basement in the EAAO south of the Lúrio Belt has been investigated for its suitability as a tectonic marker.

For this study, the Mecubúri Group has been geologically reassessed. Based on the recognition of its potential during the preceeding large-scale mapping, the Mecubúri Group has been geologically characterised and accordingly remapped, and detrital zircons have been studied geochronologically in order to gain age constraints for the maximum timing of deposition. The autochthonous meta-sedimentary rocks of the Mecubúri Group are recognised as a sequence of immature clastic sediments which sample all of the major surrounding tectonic units established in recent geological schemes. These meta-sediments overlie a lateritisised palaeo-surface of the Nampula Complex basement with coarse basal conglomerates and exhibit fining upwards. Sedimentary structures are relic. The group is considerably deformed, migmatised, and intruded by granitoid bodies and apophyses. Detrital zircon analyses constrain the deposition to a maximum age of 530 ± 18 Ma, while metamorphic monazite is dated at 499 ± 15 Ma.

The Mecubúri Group and its equivalents of the Alto Benfica Group further west are the first sedimentary records of possible molasse character that are recognised in the central high-grade portions of the EAO/EAAO, and constitute a new class of post-collisional meta-sediments for the EAAO. This establishes them as an attractive tectonic marker for studies of destructive orogenic processes. They provide some new information about the palaeo-environment in a Gondwana of high-standing topography and testify to the operation of erosional thinning, likely in conjunction with extension (mechanical thinning) in NE Mozambique. High-temperature metamorphism and remarkable deformation well after the collision indicate that destructive processes involved gravitational collapse and potentially delamination.

Having established a post-collisional tectonic marker in the Mecubúri Group, the deformation and metamorphism in the latter have been investigated (**Contribution II**) in order to characterise the post-collisional phase, and to gain local information on the effect and mode of destructive orogenic processes. The projection of these findings into the subjacent Nampula Complex basement should serve to delinate collisional and post-collisional structures, provide insights into the regional style and importance of post-collisional tectonics, and serve to characterise the latter.

The deformation in the Mecubúri Group is polyphase and locally reflects relatively high strain. Partial melting is observed during and after deformation. Related metamorphism has taken place under conditions of at least 675 °C and relatively low pressures, while the subsequent cooling, constrained by a handful of temperature-sensitive chronometers, is slow. The dominant structures in the subjacent basement of the Nampula Complex are indistinguishable from those of the Mecubúri Group (see also Fig. 5), indicating that the fabric of the basement is largely of post-collisional origin. It is thus not only not a thermal overprint of preserved Mesoproterozoic structures, but also has considerably overprinted and obliterated the structural expressions of the Late Neoproterozoic collision. Both the Mecubúri Group and its subjacent basement are infolded within a large structure with a clear signature on aeromagnetic images and satellite images. Similar, NW-SE trending structures are regionally found in an extensive domain in the Nampula Complex. These structures possibly correspond to discrete top-to-the-southwest extensional shear zones to the north of the Lúrio Belt and are interpreted as large-scale extensional folding of a hotter and more ductily deforming crust. The timing of this tectonic overprint is locally dated at ca. 515 Ma, post-dating the deposition of the Mecubúri Group only shortly. Almost identical ages from deformed intrusions in the Lúrio Belt provide evidence that simultaneous magmatism and deformation have taken place also in the belt. In conjunction with the contemporaneous high volumes of granitoids in the Nampula Complex, these observations are most satisfyingly explained with delamination, isostatic adjustment along the Lúrio Belt, gravitationally driven extension, and increased heat flow.

The identified post-collisional structures most probably reflect an original geological record comprising mid-crustal expressions of a deep-seated delamination process and can be taken to characterise crustal kinematics of delamination. Regionally, they show an intimately related thermal and tectonic overprint which shapes the present crustal structure in NE Mozambique, surpassing not only a postulated Mesoproterozoic orogeny in preserved geological record, but also the earlier collisional stages of late Neoproterozoic / early Palaeozoic orogeny.

The slow local cooling in the Mecubúri Group, post-collisional deformation, and simultaneous partial melting in the Nampula Complex have corroborated the delamination hypothesis. To fortify the hypothesis further, it is necessary to investigate what the cooling trajectories in the basement blocks on both sides of the Lúrio Belt are, and whether differential cooling across the Lúrio Belt is regionally reflected (**Contribution III**).

A relatively large data set of U-Pb titanite samples, recording cooling approximately below 660 °C, and Ar-Ar hornblende samples, recording cooling through ca. 450 °C, has been collected, in order to derive thermal histories for the major tectonic units in NE Mozambique. In data analysis, having to exercise caution with homogeneity assumptions, and to rigorously consider several tectonic units (northern and southern basement; Lúrio Belt; CDNC; klippen), the study has introduced and applied a number of techniques devised for this purpose, namely a robust treatment of a numerically restricted data set, the systematic establishment of multi-system cooling paths (integrating data from other studies), and an iterative adjustment of closure temperatures from the predicted cooling rates.

The results indicate that thermal evolution is more complex than differential cooling across the Lúrio Belt which would exhibit two different, simple trajectories on either side. Data from the Lúrio Belt itself comprise indications of repeated activity. To the north, basement data show that the late Neoproterozoic / early Palaeozoic overprint in the NW of the area did not reach high-grade conditions that were sufficient to reset titanite ages and thus may indicate the position of these sample locations outboard an orogenic front. To the south, the basement (Nampula Complex) internally exhibits regional differences in thermal evolution that were previously not recognised in lithology and structure, but coincide with different degrees of post-collisional tectonic overprint (see contribution II). Cooling patterns show that the youngest metamorphism occurred much later in the Nampula Complex than in equivalent units in the north, and that subsequent cooling took place at a slower pace in the whole Nampula Complex. This is consistent with an elevated heat flow. Accordingly, the results provide further support for the delamination hypothesis. Similar geochronological ages in granulite-facies klippen to either side of the Lúrio Belt, showing earlier cooling than in the basement rocks, support the assumption that they are remnants of the same continuous nappe complex.

In this contribution, the post-collisional development along the plate margin, in different parts of the orogen has been characterised. The thermal effects of a different interplay of orogenic decay mechanisms have been quantified and related to post-collisional structures in two differently decaying parts of the EAAO. The contribution establishes a first reliable geological record of metamorphism and cooling following delamination, relates them to an immediately adjacent undelaminated equivalent, and provides an estimate for the scales (in time and space) and effects of this process in the scheme of margin transformations.

The study demonstrates the complexity within a relatively small portion of the EAAO and of Gondwana, in an area for which a comprehensive data set of chronology over a wide temperature range (including fission-track data) has been built that is, in comparable form and extent, available in few places elsewhere. Even here, not all questions have been resolved, and new questions have emerged. An integrated interpretation with fission-track data shows that differential cooling between the basement blocks to either side of the belt persists until very recently. Difficulties to sustain exhumation control were experienced in this case of a continuous cooling difference, where the later increments could not clearly be quantified and subtracted. In addition, the nappes of the CDNC show relatively young ages in the intermediate temperature range, several tens of Ma after the main phase interpreted as collision, while no activity is recorded in its subjacent basement, and subsequent lagged cooling. This suggests a component of late modification of the the basement-cover relationships of the CDNC, and possible episodes of tectonic activity that were hitherto unknown.

To complement the studies of the post-orogenic history, and to study the rifting and passive margin evolution, comprehensive fission track studies have been carried out (**Contribution IV**). They cover a temperature range from ca. 280 - 100 °C with three different mineral sets (titanite, zircon, and apatite), and have served both to create a continuation of the cooling paths from the post-collisional phase (contribution III) and to provide control over late exhumation increments superimposed on higher-temperature chronology. In the fission-track results, large-scale patterns similar to the post-collisional data are reproduced. Titanite fission track ages in excess of 500 Ma in the northwesternmost part of the area regionally indicate relative tectonic quiescence for most of the post-orogenic time. Average cooling rates from the Ordovician to present are slow and of ca. 2 °C/Ma or less. Incipient intra-continental break-up between East Antarctica and NE Mozambique, initiating as early as in the Late Carboniferous, led to focussed denudation along the southern margin, while slow denudation is recorded north of the Lúrio Belt. The first stage of rifting, the opening of the eastern Rovuma basin, is reflected by a crustal response in a narrow (ca. 30 km) zone with numerous local transtensional faults focussing denudation, and suggests initial break-up between 200 - 170 Ma. On the southern side, the second stage with the opening of the Mozambique basin is accompanied by remarkably homogeneous enhanced cooling in the apatite data taking place at ca. 130 - 70 Ma. This uniform cooling (exhumation) stopped relatively sharply against the Lúrio Belt but reached over 250 km across the Nampula Complex and thus extended beyond the scale of a wide rifted margin. Alternative deep seated causes for this phenomenon are discussed; they focus on magmatic underplating (predominantly thermal) and differential stretching of a lithospheric mantle which has still not recovered fully from delamination (mechanical-thermal mechanism).

This contribution has characterised the two passive margins and their thermal history in relation to their geometry. It reflects erosional and mechanical thinning as competing processes along two different margins. While denudation in the Rovuma basin is fault-controlled (mechanical thinning), and small pull-apart basins attest to local erosion and sedimentation, uniform cooling of the Nampula Complex suggests a major contribution of wide-spread erosion but implies control by a deep-rooted tectonic process.

An independent study from a different perspective, with a separate method, complements the project in the form of coupled thermomechanical-petrological numerical modelling (**Contribution V**). Experiments with different initial parameters were carried out in order to constrain the principal dynamics, time scales, and (near-) surface expressions of delamination. Self-consistent numerical models start at an early stage of plate margin development, with ocean closure, so that the initial conditioning (artificial weaknesses) has lost significance when delamination initiates. Delamination was studied after external convergence conditions were lifted, and the models had begun to develop freely and self-sustaining, thus allowing to relate further observations to the characteristics of the developing orogens. Two modes have been observed. First, a mechanically activated mode in narrow, cool orogens during early collisional stages, and second, a thermally activated delamination in wide, hot orogens with plateaus and lithospheric underthrusting that initiates considerably after onset and during waning of collision. In spite of different orogenic states prior to delamination, both modes are found to lead to similar orogenic development, including a propagating separation along the Moho, heat advection with partially molten crust, and unidirectional extension. However, delamination does not necessarily mark the end of convergence and does not halt crustal thickening, although it leads to a shift in the locus of thickening. Anomalous heat flows are elevated by a factor of four and are long-lived. A major finding is that lithosphere does not replenish statically, but is dynamically detained from cooling (by self-incited, latent-adiabatic mantle convection). Instead of a 60 Ma estimate for replenishment of half of the original thickness of mantle lithosphere under static cooling, the characteristic cooling time in dynamic cases is found in the order of up to 300 Ma, after which the integrated strength of the delaminated lithosphere is still considerably lower than in undelaminated lithosphere. Simple cooling predictions on the surface mimic increased heat flow rather than uplift and produce lateral age and cooling differences which are qualitatively similar and of the same order of magnitude than recordings from NE Mozambique.

The study reproduces orogenic delamination relatively naturally with very moderate preconditioning, a self-consistency of numerical reproduction of delamination which was hitherto unavailable. Consequently, delamination can be directly related to orogenic development. Accounting for phase changes and convection in an extended upper mantle, and the important alteration of tectonic processes on the crustal level by melting and hydration, have demonstrated significant improvements in the description of the delamination process. The initiation and conditions of delamination have been elucidated and related to the states of the orogen. The contribution includes a unique investigation of the long-term development of plate margins and allows inferences on potential implications for subsequent tectonics on the time scale of the Wilson cycle. A simple, original prediction of cooling ages accompanies the long-term modelling, showing the larger importance of heat flow than of vertical movements for long-lived, lateral chronological differences.

The implications of the findings from contributions I-V have finally been combined and extended in an integrated study on the long-term development of the plate margin, which is intended to disseminate the research in summarised form at a later date (**Contribution VI**).

A comparison between the observations from NE Mozambique and independent numerical predictions is presented, suggesting that the geological development in the case study is consistent with delamination (contributions I-V). Both perspectives indicate that the lithosphere modifications are long-lasting and lead to an upkeep of increased heat flow (contributions III; V). The delaminated domain coincides with pull-apart rifting and remarkably uniform rejuvenation of fission-track ages, possibly representing differential stretching of mantle lithosphere and crust (cf. contribution IV). This may have facilitated the break-up at a high angle to the orogen along the southern margin of the study area, while break-up took place along the trend of the EAAO elsewhere. It is suggested that long-lived weakening due to longer-than-expected perseverance of a thin and hot state of delaminated lithosphere could favour later rifting, localise differential stretching, and thereby would represent tectonic inheritance. With this perspective, the Wilson cycle can be completed by the conditioning of rifting during the decay of an orogen.

The contribution is the first comparison of geological and chronological data with numerical experiments on a comparative spatial and temporal scale. At the same time, it is a unique case where the geology indicates tectonic inheritance and coupling of collisional, orogen-destructive, and break-up processes over a prolonged time period. It has an accordingly wide geodynamical scope and constitutes a novel integrated plate margin study that accounts not only for a number of linked tectonic processes, but also covers multiple methodological approaches.

2.1 Responses to primary questions

In addressing the research objectives, the modules have provided essential new contributions to most primary questions. Concerning principal scales and effects of delamination, the contributions indicate that in NE Mozambique, delamination took place between 10 and 100 Ma after collision, most likely being well developed by 30 Ma. This is consistent with numerical models, which predict delamination to be established ca. 25 Ma after the onset of collision. Following conservative estimates, the delaminated domain seems to span laterally 300-400 km into the southern EAAO, comparable with numerical estimates that range between 300 and up to 1000 km. The geological consequences are expectedly most marked in increased heat flow, but are found to incur relatively high deformation and a strong structural overprint including large-scale extensional folding. The style of extension does not exhibit clear, large detachments, possibly due to the deep levels that are exposed, or due to a thinner brittle crustal layer after exposure to basal heating. The parallellism of the southern rift margin to the study area to the main transecting crustal-scale structure that delimits the delaminated part of the orogen (locating the margin therein) suggests that inheritance of a lithospheric weakness plays an important role in the break-up some 300 Ma later. Reduced strengths are reasonable according to model predictions, and a comparison of cooling data suggests that the crust in NE Mozambique is in a similar state as in compared models.

The differential development across the Lúrio Belt, including a post-collisional phase of HT/LP metamorphism exclusively recorded to the south, is incompatible with a postulated suture along the belt if crustal thickening should have taken place to produce granulite-facies nappes to the north. If these nappes and the klippen to the south of the belt are alternatively inferred to have resulted from an earlier collision, then they contradict the possibility that a separation along the Lúrio Belt has existed thereafter. Our data indicate however that caution is needed with the interpretation of these granulite-facies nappes, as a later reactivation and limited translation can presently not be excluded. Younger metamorphism and subsequent slower cooling in the Nampula Complex are better compatible with lateral variations in the lithospheric mantle including partial delamination in the southern part, particularly since the metamorphic and structural overprints are variable, reflect only low pressures, and since identified folds of this age trend at a high angle to the suggested suture. In spite of possible obliteration, no evidence has been found for a "Kuunga" collision (in the sense of an E-W trending orogen) in NE Mozambique.

The EAAO in NE Mozambique is characterised by a multitude of differences between the respective portions north and south of the Lúrio Belt. The northern part preserves larger areas of granulite-facies rocks regarded as nappes than the south, and additional evidence has been collected that they are remnants of the same nappe complex. The orogen portion to the north retains a comparatively narrow (minimum 500 km) width and a NNE-SSW trending large-scale organisation, including possible expressions of an orogenic front. In contrast, the portion to the south shows little internal large-scale organisation, late structural and metamorphic overprints, and its bounds have not been observed within the study area. This may reflect a reshaping and widening, due to collapse, of an orogen portion in the southern part which was originally similar to that to the north of the Lúrio Belt. Post-collisional, proximal, immature siciliclastic sediments are only found to the south. Post-collisional HT/LP metamorphism including migmatisation and partial crustal melting is similarly only found in the southern part. Post-collisional cooling is slower and more variable south than north of the Lúrio Belt. Extensional structures are limited to a few recognised discrete extensional shear zones to the north, while intense small-scale structures and large-scale extensional folding are observed to the south.

The criteria that have been consulted for testing do not contradict the delamination hypothesis. Although they are individually not unique enough to conclusively prove delamination, they are capable to disprove the latter, and their unexceptional compatibility with delamination can be taken as corroboration of the hypothesis. In addition to the previously known indicators of younger metamorphic dates, and of voluminous granitoids to the south of the Lúrio Belt, support for the delamination hypothesis (Fig. 4d) stems from

- post-collisional deformation in a relatively ductile style and with extensional folding;
- contemporaneous tectonic (and magmatic) activity in the boundary shear zone;
- synchronicity of deformation and HT/LP metamorphism;
- high temperatures in relatively shallow crustal levels as shown in the meta-sedimentary rocks;
- initial variability and subsequent homogenisation of post-collisional deformation and metamorphism;
- the observation of widespread high temperatures apparently retained for almost 100 Ma after collision;
- slow cooling in comparison to the crust to the other side of the Lúrio Belt;
- and finally from the confirmation, by numerical models with a range of different initial conditions, that the geological appearance of the delamination process would be similar to the observations in NE Mozambique.

Differential cooling has been robustly derived and is found to be marked between the two crustal blocks to each side of the Lúrio Belt. However, the persistence of the difference, with the block to the north always cooling ahead in time, is more than what can be attributed to post-collisional delamination alone, and exposes the intimate linkage between (post-) collisional and break-up history.

The investigations have not succeeded in returning a simple model for the initial development and evolution of the Lúrio Belt. Although distinct phases of its formation and their superposition can be recognised, granulite-facies metamorphism, repeated activity throughout the late Neoproterozoic / early Palaeozoic orogenic cycle, and maybe thereafter, have most probably obliterated initial records of the belt. Each phase likely had a kinematic regime of its own right which presently cannot be resolved. Reconstructions of the metamorphic and thermal history indicate that the Lúrio Belt experienced conditions similar to the nappes of the CDNC during early stages of the late Neoproterozoic / early Palaeozoic orogenic cycle, but has since coherently cooled as an expansion of the Nampula Complex.

The passive margins exhibit dissimilar characteristics, different localisation, and distinct thermal effects on the immediate rift margin. While the margin to the Rovuma basin is a relatively simple transform margin, distributed and uniform Cretaceous cooling inland the southern margin is not compatible with simple rift shoulder uplift. A deep-rooted process of debatable nature is postulated to account for this signal. Although no compelling evidence is available at present, it is likely that destructive processes of the orogen have had a substantial influence on the break-up, and that inheritance of a deep-rooted preconditioning is reflected.

The work contained in this thesis includes many of the approaches that are available to the study of delamination. As with underplating and other processes, it is difficult to observe and verify delamination from the surface, and the application of geological delamination models to case studies will likely remain subject to contestation. However, the contributions have characterised a probable case of delamination and highlighted possible context and possible scales of this process. They have accentuated the potential importance of delamination in more than punctiform process studies, as it sustainably alters the depth layering of the uppermost Earth and the thermal and rheological properties of its shell.

2.2 Limitations and suggested improvements

In the case of NE Mozambique, no concluding answer is possible as to the origin and the early kinematics of the Lúrio Belt. After decades of geological and now geochronological studies, this should be taken as cautionary note when postulating continuations in either direction, keeping in mind which stage and geological expression of the belt should be specifically referred to. Within the study area, the internal continuation has not been attestable for all characteristics of the belt in the view of geologists after several local field seasons. More prudence should be practised in even larger-scale correlations.

The work has identified a major enigma in the post-collisional development of the CDNC and similar complexes of nappe affinity to both sides of the Lúrio Belt, perhaps reflecting an unrecognised, late modification by eduction[2], extensional back-sliding, or transcurrent reactivation. Detailed studies in the field are necessary in order to address these and numerous other puzzles, but should be encouraged by the yielding example of the Mecubúri Group. Even there, sedimentological studies or a detailed re-mapping according to facies would

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[2] inclined exhumation away from a subduction/collision environment: e.g., Andersen et al. (1991)

likely further the understanding of the post-collisional palaeo-environment in this part of Gondwana and of the EAAO.

In completion of delamination and inheritance studies in NE Mozambique, seismic investigations of the lithosphere-asthenosphere boundary would be of great value. Additional chronological data in the temperature range between 300 - 400 °C would serve to improve the construction of cooling trajectories and to constrain the transition from post-orogenic cooling to temporary tectonic quiescence.

For the study of the EAAO in Gondwana, it would be beneficial to gain additional data, in particular detailed field observations, on the supposed contact of the principal orogenic systems. One such crucial point could lie west of NE Mozambique where the possible continuation of the Lúrio Belt would abut the Zambesi Belt but is bisected by the East African rift system.

A study of collapse in Madagascar and Sri Lanka, in a similar style as carried out here, would together with Antarctica allow a valuable comparison of previously adjacent continental fragments and might provide additional constraints on the operation and distribution of destructive orogenic processes. In general, in expansions of reviews that focussed on the inferred peak metamorphism, a review of high- to intermediate temperature cooling might prove more unique (since lagging behind peak conditions would be a part of the comparison) and could make an original contribution.

The methodological improvements for the analyses of data as presented here could be taken further. Robust $t - T$ trajectories could be refined to account for every grain with its grain size and according cooling temperature individually. Propagation and mapping of probabilities and uncertainties also in temperature direction, by forward modelling in the style of fission-track length distributions, might greatly enhance the derivation of probable cooling histories (for a preliminary proposal, see Fig. 7).

In general, the contributions suggest that a general strategy of employing as many chronometers as possible is beneficial, even if only a small number of samples per system can be analysed. Ultimately, major developments would however be necessary to allow for a true thermal backstacking in which lower-temperature exhumation could progressively be subtracted from higher-temperature records.

Numerical models of delamination could be run with a wealth of additional parameters to study. Melt extraction might be included to reproduce the formation of separate granitoid bodies. Three-dimensional models may predict delamination structures or at least the full strain ellipsoid for extension above delamination, and test the likelihood of extensional folding. The prediction of chronometers could be significantly improved by adapting a more sophisticated method for the determination of ages, would however remain contingent on a high-resolution surface, and might benefit from refined surface processes. Age predictions could be moved beyond a simple closure concept and allow for partial reheating and opening of minerals to isotopic/elemental diffusion. However, a combination of all improvements, in high resolution, would quickly bring present computational resources to their limits.

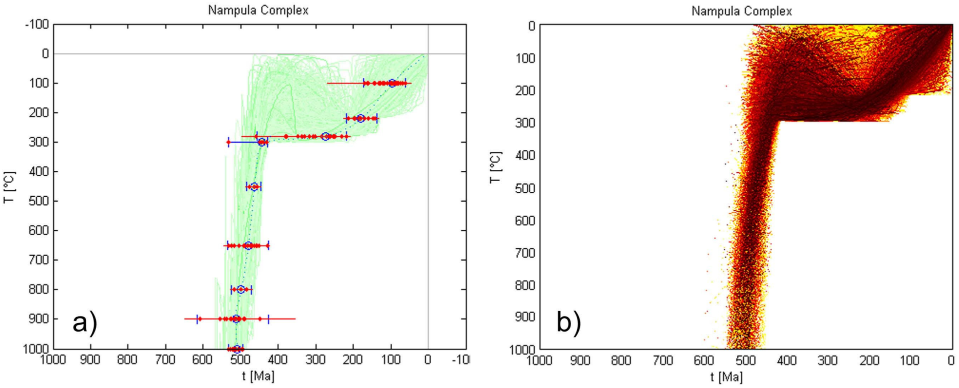

Fig. 7. Preliminary "thermal modelling" of combined chronological data based on robust statistics (see contribution III). a) Probabilities are propagated by forward modelling (testing of fit of random $t - T$ trajectories) to allow for intermittent cooling and reheating. Since the principle is the same, future improvements could include kinematic modelling of fission track populations for apatite and inclusion of the distribution fit into the probability measure. Red dots and bars: individual measurements. Open blue circles and blue bars: median of probability density distribution for chronometer, and 2.5/97.5% percentile of cumulative probability density. Dotted green line: direct fit through medians. Solid green to white lines: paths shaded according to combined percentile / cumulative probability at which chronometers are passed, green - good fit, white - bad fit. b) Coverage and mapping of probabilities propagated along paths from a). Black - high probability, yellow - low probability.

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