Two years ago, our group initiated an original project aiming at the reconstitution and the comprehension of the evolution of the topography of a continent over the last 250 My. Our goal is to quantify the growth of long wavelength (1000 km) topography and the associated rates of uplift over the last 250 My at the scale of a continent – Africa – and to understand their relationship with underlying mantle dynamics. Our approach involves the joint acquisition of relevant geological data (from sedimentology, stratigraphy, structural geology, thermochronology, etc..) and use of state-of-the-art numerical modelling tools.

The evolution of the Earth's topography over geological time scales is indeed very poorly known. However, it is critical to understanding surface processes such as climate change, sea level variations, global geochemical cycles, biodiversity evolution, but also the nature of the mantle and lithospheric processes that control the topography. The past topography of the Earth is the product, and thus the record, of the interactions between the solid Earth and its surficial envelopes occurring through geological time. However, the few available reconstructions are mainly qualitative, and usually correspond to "rules of thumb" deduced from present-day relationships between relief and tectonic setting. Defining a more rigorous method for a quantification of paleotopography is clearly lacking and is yet of primary importance.

Most studies of past topography reconstruction have focused on orogenic areas. Few efforts have been devoted to characterizing the more subtle long wavelength topography, such as the doming or plateau uplift of continental areas at the 1000 km wavelength. The amplitude of uplift and subsidence of large regions of the African continent during the Meso-Cenozoic is substantial, yet poorly understood. However, for a variety of reasons, it offers an ideal opportunity to quantify its evolution through geological times: Africa is surrounded by passive margins and bears several intracratonic basins ensuring an excellent preservation of the product of continental erosion and the continent has remained relatively fixed with respect to the underlying mantle at least since the end of the Paleozoic. It is commonly agreed that the long wavelength pattern in the topography reflects mantle dynamics. However, the exact nature of these mantle processes remains unclear (dynamic topography, delamination of the mantle lithosphere, thermal expansion). Key in this debate is the age and the dynamic of the topography.

Our project is subdivided into two parts. In a first step, we have tried to quantify the Meso-Cenozoic surface uplift rates and topographies of the African continent on the basis of (i) new-style paleogeographic reconstructions including, for example, the geometry of paleocatchments, (ii) measures of terrigenous sedimentary fluxes and (iii) thermochronological data. We use a new numerical model of sediment production and transport at the continental scale currently developed at Géosciences-Rennes to perform the quantitative inversion of the observations to yield estimates of past topography. In a second step we aim to determine the geodynamical processes responsible for the anomalous topography of the African continent and its evolution through time.

One expected deliverable of this project will be a unique set of continental-scale, paleotopographic maps based on a large, novel paleogeographical dataset of Africa over the last 250 My made available to the entire community as an GIS (ArcGIS) database.

One of the challenges and strengths of this project is to get geologists and modellers to work together on a well-defined objective. This symbiosis, initiated in Geosciences Rennes has rapidly reached limitations, our group not covering the whole disciplinary and regional knowledge required. For these reasons, we have decided to organize an international workshop whose objectives are to (1) present our approach, (2) confront our preliminary results to the best regional expertise, (3) discuss the geodynamic scenarii to be tested, (4) improve our methodological approach, and last but not least, (5) invite scientists interested to join the project in one way or another.

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François Guillocheau
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PROGRAMME

Tuesday November 13th 2007 @ Université de Rennes 1, Campus de Beaulieu

10h00 to 12h00 Welcome
in: Hall of CAREN, bâtiment 14b

12h30 Onsite lunch

14h00: J. Braun & F. Guillocheau *"The TopoAfrica project"*
in: Amphihéatre Louis Antoine, bâtiment 2
15h00: M. Brunet *"On the track of a new paradigm for the cradle of mankind...in Chad, Central Africa "*

16h00 "Ice Breaker""
in lobby of Amphihéatre Louis Antoine, bâtiment 2

18h00 Departure for downtown Rennes *(bus)*
18h30 Visit of Espaces des Sciences and Planetarium (*downtown)*
20h30 Diner Restaurant LA CHOPE

Wednesday November 14th 2007 @ Maison Internationale de Rennes (downtown)

SESSION 1 **Mantle and Lithosphere Dynamics**
8h30 Introduction: K. Gallagher / R. Brown
8h45 A. Forte *"Tomography based convection modelling of mantle dynamics below the African plate: implication for time dependent dynamic surface topography".*
9h45 S. Fishwick *"Seismic studies of the African continent and a new surface wave model of the uppermost mantle".*
10h45 Coffee Break
11h15 D. Bell *"title"*
12h00 D. Rowley *"title"*

12h45 Onsite lunch

14h00 Discussion session 1

SESSION 2: **Volcanism in Africa over the last 250 Myr**
14h00 Introduction: F. Guillocheau
15h15 V. Courtillot *"Volcanic eruptions, global change and evolution of species"*
16h15 Coffee Break
16h45 H. Bertrand *"CAMP and Karoo: the two largest igneous provinces of the African plate"*
17h45 Discussion

free evening

Thursday November 15th 2007 @ Maison Internationale de Rennes (dowtown)

SESSION 3: **Climatic and geological evolution of Africa over the last 250 My**
8h30 F. Guillocheau *"Palaegeography of Africa through Meso-Cenozoic times: a focus on the continental domain evolution"*
9h30 M. de Wit *"Tracking the Kalahari epeirogeny: from fission tracks and cosmogenic dating to molecular clocks"*
10h30 Coffee Break
11h00 Y. Donnadieu *"A GEOCLIM simulation of climatic and biogeochemical consequences of Pangea break up"*
12h00 Discussion

12h30 Onsite lunch

SESSION 4 **Relief dynamics at continental scale**
13h30 D. Rouby **"***The sedimentary supply of African sedimentary basins over the last 250 Ma"*
14h15 M. Summerfield *"title"*
15h15 T. Partridge *"The tectonics and geomorphology of Africa: an overview"*
16h15 Coffee Break
16h45 N. White *"Scales of transient convective support beneath Africa"*
17h45 Discussion

20h00 Diner Restaurant LA CHOPE

Friday November 16th 2007 @ Maison Internationale de Rennes (downtown)

SESSION 5: **Alteration and transport dynamics at the continental scale**

08h30 M. Simoes *"Providing tools to quantify the kinematics of uplift of Africa over the last 200 Myr."*

09h30 A. Beauvais *"Age and nature of lateritic weathering, erosion rates and long-term morphogenesis"*

10h30 Coffee Break

11h00 J. Gaillardet *"Rates and styles of continental denudation: Clues from river geochemistry"*

12h00 Discussion

13h00 Onsite lunch

14h00 bus to the Mont Saint Michel

16h30 Visit of the Mont Saint Michel Abbaye

20h00 Diner in Cancale

Quantifying the Evolution of the African Topography over the last 250 My: from the sedimentary record to mantle dynamics

François Guillocheau, Jean Braun, Martine Simoes, Delphine Rouby, Cécile Robin, Olivier Dauteuil and Kerry Gallagher

Géosciences Rennes, Université de Rennes 1, F 35042 Rennes Cedex, France

The goal of this project is to quantify the growth and decay of long wavelength (1000 km) topography and the associated rates of uplift over the last 250 My at the scale of a continent – Africa – and to understand their relationship with the underlying mantle dynamics over such a period of time. Our approach involves the joint acquisition and compilation of relevant geological data and use of state-of-the-art numerical modelling tools.

Why reconstruct past topography?

The evolution of the Earth's topography over geological time scales is poorly known. However, it is critical to improve our understanding of the dynamics of processes taking place at the surface of the solid Earth, such as climate change, sea level variations, global geochemical cycles, biodiversity evolution, but also the nature of deeper processes in the mantle and lithosphere that may control the growth of the topography. Clearly, the past and present topography of the Earth is the product, and thus the record, of the interactions between the solid Earth and its superficial envelopes occurring through geological time.

Few studies have been carried out to constrain even the first order features of the Earth'paleotopography; these currently take the form of world-scale paleogeographic maps (Smith et al., 1994, Ziegler et al., 1997, Scotese, 2002, 2004). These reconstructions are mainly qualitative, and the arguments on which they are based are sometimes poorly presented and usually correspond to "rules of thumb" deduced from present-day relationships between relief and tectonic setting (Scotese, 2004). Defining a method for a more rigorous quantification of paleotopography is clearly lacking and is yet of primary importance.

Example of a new style paleogeographic map of the African continent showing the varied and novel information it contains such as the geometry of the continental-scale paleodrainage and the erosional vs depositional state.

Why Africa?

Most studies of past topography reconstruction have focussed on orogenic areas and the growth of mountain belts in tectonically compressive environments. Few efforts have been devoted to characterizing the more subtle, long wavelength topography, such as the doming or plateau uplift of continental areas at the 1000 km wavelength. The amplitude of uplift and subsidence of large regions of the African continent during the Meso-Cenozoic is substantial, yet poorly understood. However, for a variety of reasons, it offers an ideal opportunity to quantify its evolution through geological times: Africa is surrounded by passive margins and bears several intracratonic basins ensuring an excellent preservation of the product of continental erosion; the continent has remained relatively fixed with respect to the underlying mantle at least since the end of the Paleozoic; it has undergone only limited and localized compressional tectonic activity (mainly in the Atlas). Consequently, it is commonly agreed that the long wavelength "basins and swells" pattern in the topography (e.g. Congo depression vs. South African Plateau) is linked to mantle dynamics (Nyblade & Robinson, 1994; Conrad and Gurnis, 2003; Nyblade & Sleep, 2003). However, the exact nature of these mantle processes remains unclear (dynamic topography, delamination of the mantle lithosphere, thermal expansion). Key in this debate is the age of the topography, including the contribution resulting from Gondwana breakup, and the rate of growth and decay of the long wavelength features. More recent and localised topography, whose age and causes are relatively well known (i.e., East African Rifting, Neogene volcanism, and North African collision), is superimposed over the long wavelength plateaus and depressions.

The project

This project is subdivided into two parts: (1) quantifying the timing and amplitude of the birth, growth and decay of the African topography over the last 250 Myr, and (2) assessing the geodynamical processes causing the topography.

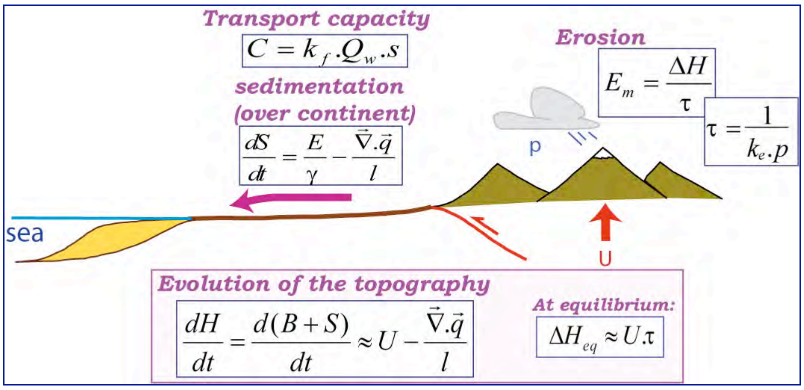
1. Quantifying the timing and amplitude of the African topography. In a first step, we aim to quantify the Meso-Cenozoic surface uplift rates and the resulting topography of the African continent on the basis of (i) new-style paleogeographic reconstructions yielding, for example, the geometry of paleocatchments, (ii) measures of terrigenous sedimentary fluxes and (iii) thermochronological data. The construction of these databases and maps requires new, targeted field observations. Because landscape response to spatially varying tectonic (mantle) and climatic forcing can be quite complex, a direct inversion of the data into estimates of paleotopography is not possible. We have developed and are now making use of a new numerical model of sediment production and transport at the continental scale that forms the basis of the quantitative inversion of the observations to yield estimates of past topography. This model is validated through a series of local field projects targeting the quantification of the response of the natural system to external forcing.

2. The geodynamical processes causing the topography. In a second step, we aim to determine the geodynamical processes responsible for the anomalous topography of the African continent and its evolution through time. We propose to use state-of-the-art numerical models to assess the topographic signature of different mechanisms originating in the mantle beneath the continent. Different hypotheses will be tested including the dynamical effect of a large mantle upwelling; the delamination of the mantle part of the continental lithosphere; magmatic underplating or thermal expansion associated with an array of smaller mantle plumes rising beneath the continent; dynamic rebound associated with the detachment of a subducting slab; and isostatic flexural effects linked to continental rifting and the breakup of Gondwana. These hypotheses differ in their implications on the amplitude, lateral extent, timing and rate of growth/decay of the topographic signal; the paleotopographic reconstructions constructed in the first part of the project should provide discerning and lead to objective arguments for or against each of them.

One of the challenges and strengths of this project has been to get geologists and modellers to work together on a well-defined objective. This symbiosis is already well under way at Géosciences Rennes. The inclusion of international experts in numerical modelling and mantle dynamics in a research team otherwise composed of stratigraphers, sedimentologists, field geologists and geophysicists, is further indication of the novelty of this multi-disciplinary approach where data collection and modelling will go and progress hand-in-hand.

Main outcomes of this project

- To build a set of unique continental-scale, paleotopographic maps based on a large, novel paleogeographical dataset of Africa over the last 250 My.
- To develop and use a new methodology to extract quantitative paleogeographic and paleotopographic constraints from the geological record.
- To develop a new parameterization of erosion and sediment transport at large spatial and temporal scales, by confronting existing laws with the geologically-documented dynamic response of natural systems to external forcing processes.
- To selectively extend the existing database of low temperature thermochronology as a quantitative constraint on long-term erosion.
- To determine which, if any, of the currently competing models for the complex vertical motions of the surface of the African continent is consistent with the new dataset.
- To progress in our understanding of how surface (dynamic) topography is created by mantle processes and, doing so, to improve our constraints on mantle viscosity and density structure.



The new numerical model for continental-scale erosion and sediment transport developed in the framework of this project. Sediment production (by physical erosion E_m) is assumed proportional to mean elevation above a regional base level (ΔH) and inversely proportional to a time scale, τ. This time scale is itself inversely proportional to local precipitation rate (p) and bedrock erodability (k_e). Sediment transport is limited by runoff (Q_w) and local slope (s). An imposed surface uplift function (U) drives the model.

ON THE TRACK OF A NEW PARADIGM FOR THE CRADLE OF MANKIND… IN CHAD, CENTRAL AFRICA …

Michel Brunet (1)

In the 80's, early hominids are known in South and East Africa but the oldest being in East Africa led Coppens (1983) to propose his "East Side Story" original savannah hypothesis.

From 1994 the M.P.F.T.[2] digging in Djurab desert (Northern Chad) unearthed successively a new australopithecine, *Australopithecus bahrelghazali,* nicknamed Abel (biochronologicaly dated to 3-3.5 Ma), the first ever found West of the Rift Valley (Brunet et al., 1995) and a new hominid (nicknamed Toumaï) *Sahelanthropus tchadensis* Brunet *et al*., 2002 from the late Miocene, biochronologicaly dated close to 7 Ma (Vignaud *et al.*, 2002). This earliest hominid is a new milestone suggesting that an exclusively southern or eastern African origin of the hominid clade is unlikely to be correct.

Since 1994, our roots went deeper, from 3.6 Ma to 7 Ma today, with three new Late Miocene species: *Ardipithecus kadabba* Haile-Selassie, 2001 (5.2–5.8 Ma, Middle Awash, Ethiopia) and *Orrorin tugenensis* Senut *et al.*, 2001 (ca. 6 Ma, Lukeino, Kenya) while the oldest (ca. 7 Ma) is the Chadian one which has a scientific impact similar to that of *A. africanus* Dart, 1925.

***S. tchadensis* displays a unique combination of primitive and derived characters that clearly shows that it is not related to chimpanzees or gorillas, but clearly suggests that it is related to later hominids, and temporally close to the last common ancestor between chimpanzees and humans (Brunet *et al.*, 2002 & 2005; C. P. E. Zollikofer & *al.*, 2005). In Chad, the Late Miocene sedimentological and paleobiological data are in agreement with a cyclical mosaic of environments (Vignaud et *al.*, 2002, Schuster et *al.*, 2006)). Today the Okavango Delta (Central Kalahari, Bostwana) appears to be a good analog with a similar mosaic of lacustrine and riparian waters, swamps, patches of forest, wooded islets, wooded savannah, grassland and desertic area (Brunet et *al.*,2005). Among this mosaic the precise habitat of Toumaï is still in progress but probably, as the others known late Miocene Hominids, a wooded one. Moreover these three late Miocene hominids are probably usual bipeds. So the models that invoke savannah in the hominid origin must be reconsidered. Now, it appears that the earliest hominids inhabited wooded environments and were not restricted to Southern or Eastern Africa but were rather living in a wider geographic region, including also Sahelian Africa: at least Central Africa (Chad) and probably Libya.**

So, the early hominid history must be reconsidered within a completely new paradigm.

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Popular works:

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Science et vie Junior : Supplément +DVD , Mars 2006 ;
Michel Brunet : D'Abel à Toumaï, Nomade Chercheur d'Os, Editions Odile Jacob, 15 Juin 2006 ;
DVD Toumaï le Nouvel Ancêtre (film de 80', plus le making of de 26' & Sur la piste d'Abel, film de 52') Production Gédéon Programmes, Paris, Mars 2006.

Tomography-Based Convection Modelling of Mantle Dynamics Below the African Plate: Implications for Time Dependent Dynamic Surface Topography

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Since the late 19th century, physical geographers and dynamic geologists have recognised that the African continent is unique and peculiar by virtue of its widely distributed late-Cenozoic hotspot volcanic activity, anomalous elevation, basin and swell topography and the active African rift system that runs approximately 6000 kilometres from Lebanon in the north to Mozambique in the south (*e.g. Burke 1996*). No other continent on Earth displays this pervasive influence of recent hotspot magmatism, tensional stresses and recent continent-scale uplift. The outstanding problem of African geodynamics is to relate these surface processes and their spatial-temporal evolution to the dynamics of mass and heat transfer in the lithosphere and deeper mantle below the African plate. Over the past two decades a wide variety of seismic tomography models have consistently revealed long wavelength images of a large low-velocity (and presumably high-temperature) anomaly below southern Africa extending from the core-mantle boundary to the mid mantle. This deep-mantle seismic anomaly has been interpreted as the possible origin of the "African Superswell", the large-scale anomalously high topography which extends from southern African to the Red Sea along the Great Rift Valley (*Nyblade & Robinson 1994*). This hypothesis has been supported by independent mantle flow calculations of the origin of African Superswell topography using long wavelength global tomography models (*e.g. Hager et al. 1985, Lithgow-Bertelloni & Silver 1998*). Initial estimates of the time-dependent evolution of the dynamic topography of Africa have also been modelled using these tomography-based mantle convection models (*e.g. Gurnis et al. 2000; Conrad & Gurnis 2003*). The most direct expression of the dynamical interaction between the mantle under the African continent and the overlying crust is in terms of the mantle flow field and associated lithospheric deformation rates and these have been explored using long wavelength tomography-based mantle flow calculations (*Forte et al. 2002; Behn et al. 2004*).

To date all tomography-based numerical investigations of mantle dynamics beneath the African plate have been based on long wavelength global tomography models (*e.g. Ritsema et al. 1999*) which are only capable of resolving structure with horizontal wavelengths which are generally in excess of 2000 km. This spatial resolution is simply too low to map out a sufficiently detailed connection between the surface manifestations of African hotspot magmatism and related topographic anomalies (e.g. the late-Cenozoic volcanic domes, African Rift topography) and the sublithospheric mantle flow pattern below the African plate. A nearly order of magnitude increase in horizontal resolution is necessary to discern the asthenospheric flow patterns below the Rift Valley system and the major volcanic domes (e.g. Hoggar, Tibesti, Kenya) which characterise Africa's unique physiography. Such high resolution mantle flow models would provide valuable constraints on the evolution of Cenozoic magmatic activity on the African plate (*e.g. Ebinger & Sleep 1998*) as well as improving our understanding of the detailed evolution of African dynamic topography. The latter is of special relevance to current efforts to understand the Cenozoic evolution of drainage of the major African river systems (*e.g. Moore & Blekinsop 2002, Goudle 2004, Walford et al. 2005*). To address these outstanding challenges we require tomography-based convection models with horizontal resolutions characterised by half-wavelengths of the order of 100 km.

Substantial progress has recently been made in deriving seismic tomography models which approach the horizontal resolutions needed to address the modelling challenges outlined above. A new series of simultaneous inversions of both global seismic and surface geodynamic data sets, in which mineral physical constraints on mantle thermal properties are also included, have been carried out with substantially higher spatial resolution than has been possible in the past (*Simmons et al. 2007*). These new tomography models provide significantly enhanced maps of the immense thermochemical plume which stretches upward from the core-mantle boundary under southern African and extends into the upper mantle. These tomographic inversions yield 3-D distributions of mantle density anomalies which includes both thermal and compositional heterogeneity and it therefore enables us to explicitly incorporate, for the first time, the stabilising effect of compositional buoyancy in the continental tectosphere and in the deep lower mantle. These new inferences of the 3-D structure below the African plate are used in a new series of numerical simulations of the present day mantle convective flow below the continent. We obtain a remarkably detailed pattern of shallow, sublithospheric flow below Africa and we trace its dynamical relationship to the deep-mantle flow driven by the African superplume. The asthenospheric flow patterns show clearly focussed upwellings below all the major late-Cenozoic volcanic domes on the African plate. These predictions of mantle flow are used to predict the present-day dynamic topography of the African continent shown below in Figure 1. The same flow predictions are also used as the starting conditions for backward convection simulations which allow us to model the time evolution of dynamic topography on the African plate.

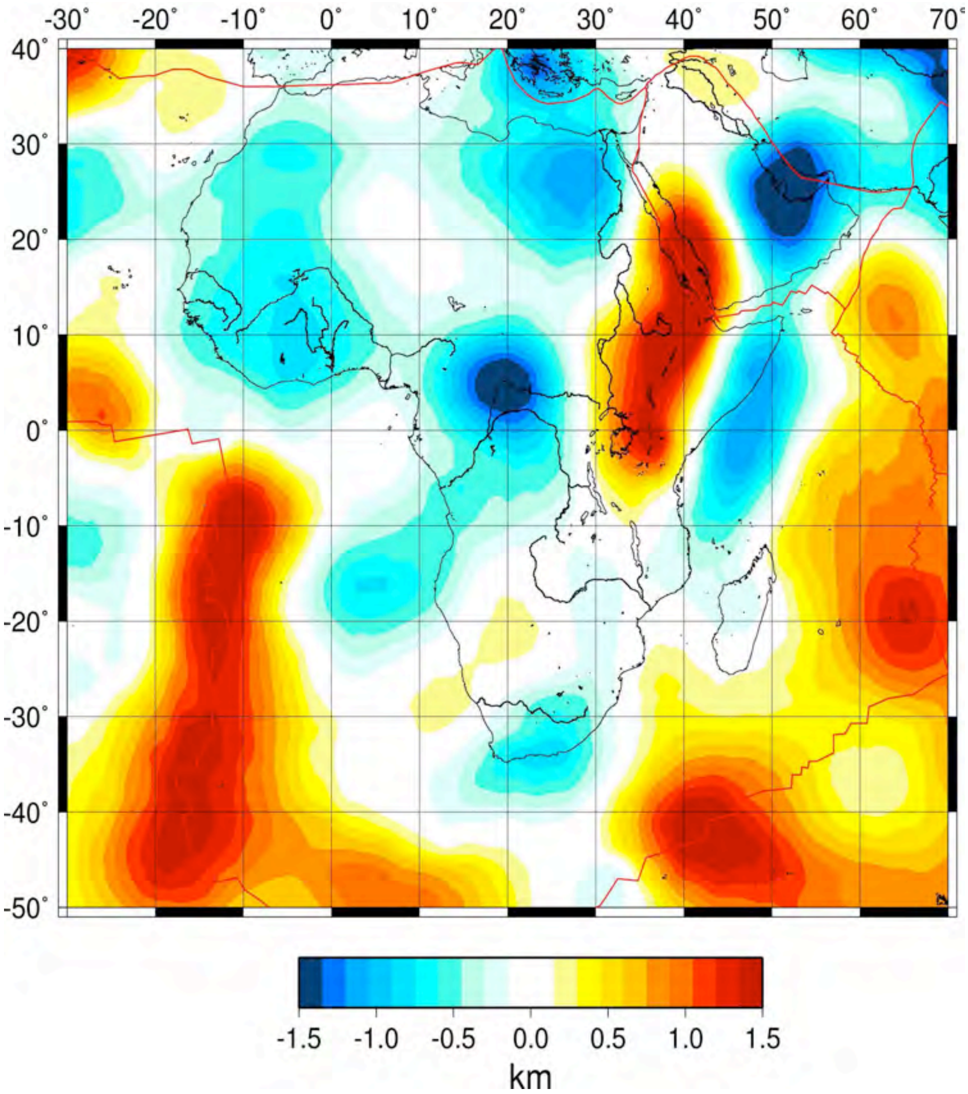

Figure 1: Dynamic Topography of the African Plate predicted by a viscous flow model based on the tomography-derived mantle density anomalies obtained by *Simmons et al.* (2007). All topographic undulations shown here are with respect to a global horizontal mean value of 0.

Seismic studies of the African Continent and a new Surface Wave Model of the Uppermost Mantle

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Abstract: The African continent remains a challenging location for understanding the structure of the upper mantle and the dynamics of the Earth. There are a limited number of permanent seismic stations and, presently, publicly available data from temporary deployments are only available from the eastern and southern parts of the continent. Global and regional studies relating dynamic topography to seismic studies have predominately focussed on the large slow wavespeed anomaly in the lower mantle (e.g., Lithgow-Bertelloni and Silver, 1998; Gurnis et al., 2000; Simmons et al., 2007). Here, a new tomographic model of the uppermost mantle will be presented with discussion on how the wavespeed anomalies can be combined with other geophysical techniques in order to give indications of the interaction between the convecting mantle and the overlying lithosphere. Finally, the need, and difficulty, of combining the different seismological models and techniques will be addressed.

New Tomographic Model of the Uppermost Mantle beneath Africa: The tomographic model has been built using publicly available data from southern Europe, Africa and Arabia. Within the African continent there are few permanent seismic stations, but the data available from the Kaapvaal, Tanzanian and Kenya/Ethiopia projects is crucial in obtaining a good distribution in path coverage (figure 1). In the near future, data will be accessible from experiments in the Cape Verde Islands and in the Dhofar region, using these data will continue to improve the resolution and reliability of tomographic models of Africa. In the longer term, the ongoing Africa Array project (http://africaarray.psu.edu) is likely to make a considerable difference in the reliability of detailed models of the structure of the mantle beneath the African continent.

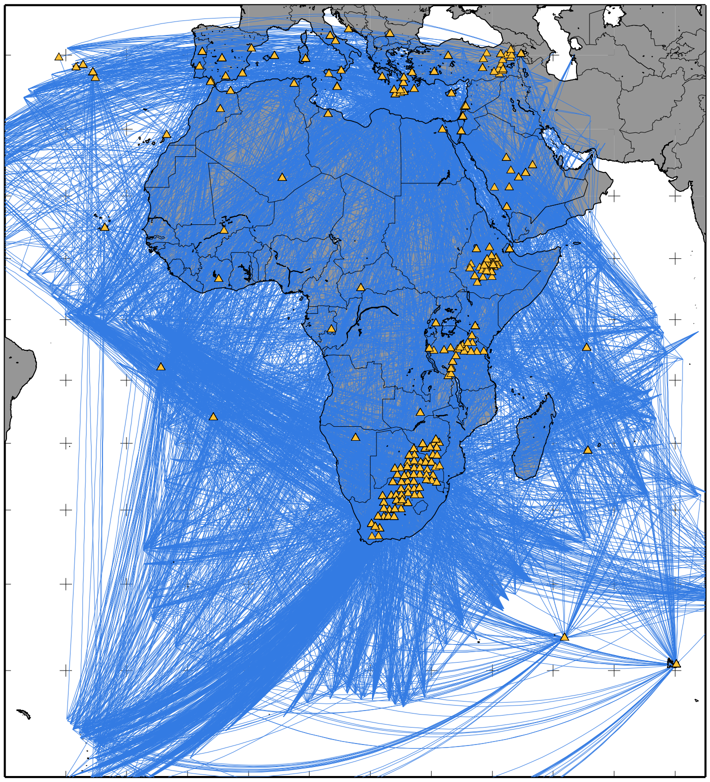

Figure 1: Path coverage used within the tomographic inversion. Location of the broadband seismometers are shown with yellow triangles. The high density of stations from the Kaapvaal, Tanzanian and Ethiopian experiments can be clearly seen

The model presented here uses the waveform inversion methods of Debayle (1999) and Fishwick et al., (2005). A semi-automated inversion procedure controls the calculation of path average 1D models between source and receiver. For each path, multiple starting models are employed to improve the reliability of the 1D model that is used within the tomographic inversion. The emphasis is placed on the quality of the data, rather than simply increasing the quantity of data, as seems to currently be a trend in some areas of tomography. The set of all such path average models (figure 1) are then used within a tomographic inversion to locate regions with fast or slow wavespeeds. The 1D models are defined at 25km intervals, and at each depth a 2D model is independently calculated. We use a two-step inversion scheme to produce the tomographic images. In the first step the reference model is a uniform velocity and, using a spline function defined with knot points at 6° intervals, we invert for the large scale structure. In the final inversion, we damp back towards the large features but use smaller knot spacing (3°) to image more detailed structure.

Figure 2 shows the results from the inversion procedure, for both the large scale and the detailed structure, at the depths of 75, 150 and 225 km. At 75km depth, the striking contrast between the slow wavespeeds beneath the mid ocean ridge and the faster wavespeeds below the older oceanic floor are apparent. Within the continent the difference between cratonic regions and active areas is also visible. By 150km depth the range of seismic wavespeeds is at it's greatest, with a total variation of more than 15%. At this depth, the location of diamondiferous kimberlites tends to be on the edge of the regions of fast wavespeeds. At 225km depth the velocity contrasts are significantly reduced, with only small regions of the continent showing faster velocities typical of thick lithosphere. The absence of fast velocities in the region beneath the Tanzanian Craton is particularly noticeable, this is in agreement with local surface wave studies (Weeraratne, 2003), however the velocities in this model are not as low as in the local model.

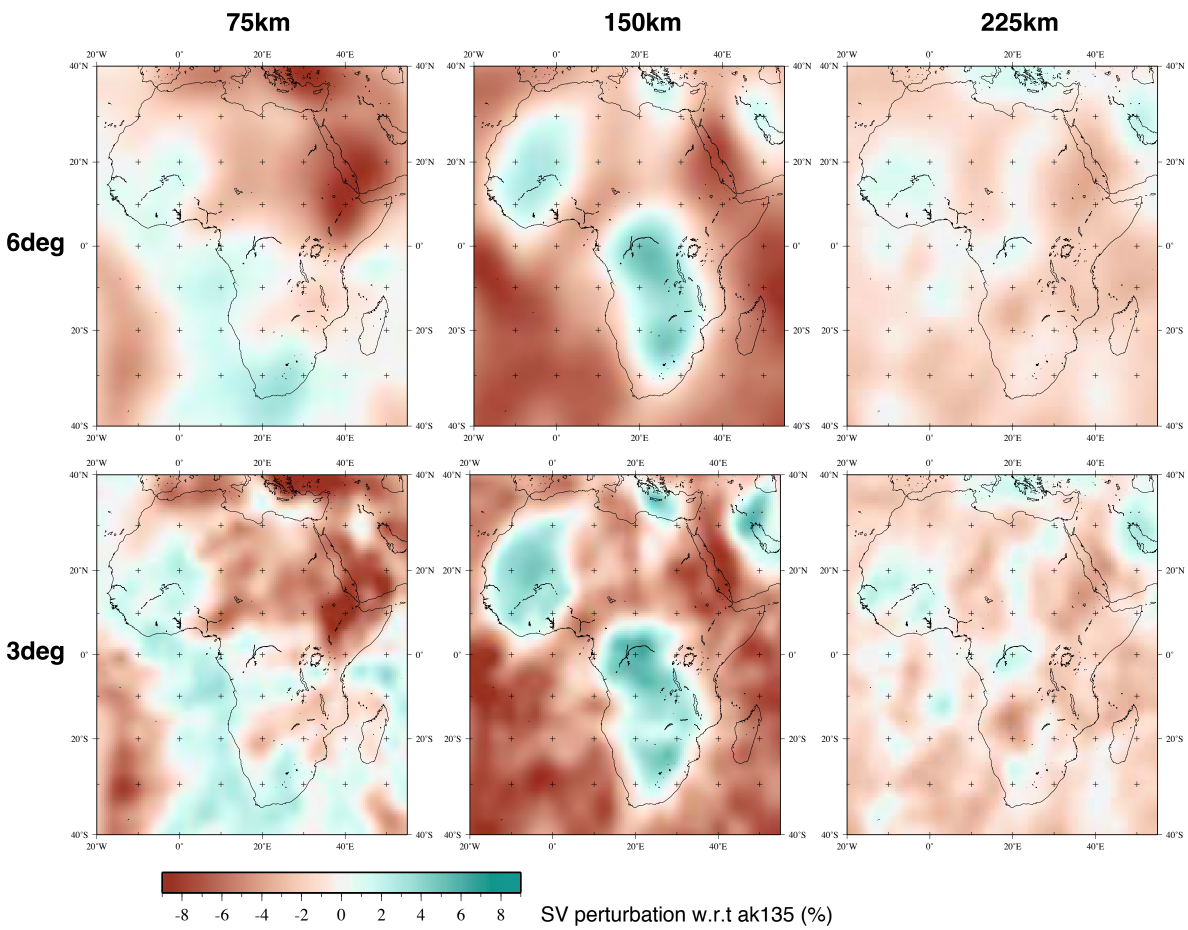

Figure 2: Tomographic model at 75, 150 and 225km depth. The colour scale remains the same at all depth intervals, velocities are plotted as perturbations from the reference model ak135

From a geodynamic perspective, some of the smaller scale, slow wavespeed features are of particular interest. The slow wavespeeds may be caused by higher temperatures, and we are interested in investigating whether these structures can be linked to other geophysical measurements and geological observations to improve our knowledge of the dynamics in the uppermost mantle. Figure 3 shows the average velocities at 100-175km depth, with the long wavelength free air gravity anomaly overlain. In northern Africa the strong gravity highs are related to the volcanic regions of Hoggar and Tibesti, and there are slightly lower wavespeeds observed beneath these regions. Many of these slow wavespeeds do not extend particularly deep within the model, although whether this is a question of resolution remains an issue. Work is in progress to look for correlations between the wavespeeds, gravity anomalies and geochemical signatures for these volcanic areas. On the west coast of southern Africa the correlation of the slowest wavespeeds and gravity high can also be related to regions of recent uplift, as determined by the modelling of seismic velocity profiles along the shelf of the West African Salt Basin (Al-Hajri et al., in preparation).

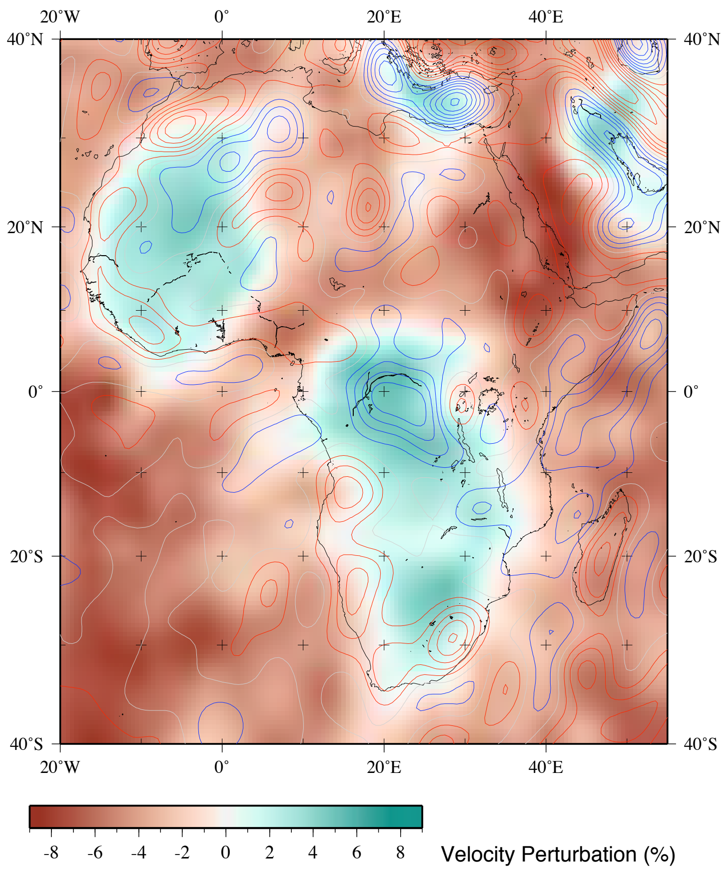

Figure 3: The average shear wavespeed from the tomographic models between 100 and 175km depth, again plotted as a perturbation from the reference model ak135. Long wavelength (fi ltered around a wavelength of 800km) free air gravity anomalies from GRACE, GGM02S (Tapley et al., 2005) are also plotted. Red contours indicate positive gravity anomalies, blue contours indicate negative gravity anomalies.

It appears that there are a number of small-scale features in the tomographic model of the upper mantle beneath Africa that can be related to upwelling. Fundamental questions remain as to the extent and cause of these features. Is there a direct link to upwelling from the lower mantle and, thus, through the transition zone? What role does the edge of the lithosphere play in guiding, or creating, the convection within the uppermost mantle? Is temperature the best explanation for the wavespeed anomalies, or are melting and compositional variation also required? Other seismological techniques, such as seismic anisotropy, may give more information on patterns of flow. Receiver functions and precursors can shed more light on the nature of the discontinuities within the mantle. However, one of the major challenges for seismologists, and geoscientists in general, is to find methods which can combine these different techniques into models that are also compatible with our understanding of the physical characteristics of the Earth. Through this combined approach, and with continued effort towards improving the distribution of seismometers across the continent it should be possible to build up a more detailed picture of the dynamics beneath Africa.

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Volcanic eruptions, global change and evolution of species

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Abstract:

Our group proposed in 1986 that the Deccan traps of India had been co-eval with the Cretaceous-Tertiary mass extinction, had lasted less than 800 kyears, straddling the KT. In 1995, Bhandari and colleagues showed that the iridium level marking the Chicxulub impact could be found in the Deccan and was sandwiched between flows, demonstrating that they were co-eval events but that volcanism had started first and could not be a consequence of impact. Since then, many groups have contributed to dating more precisely continental flood basalts around the world and found that there was almost a one to one correspondance between flood basalts and mass extinctions (but not impacts, except for the KT) : for a recent review see Courtillot and Renne (2003). In recent years, a number of significant advances have been made. It has been shown in the case of the historically large but geologically very small Icelandic Laki eruption of 1783 that such eruptions could inject large amounts of sulfate aerosols all the way to the stratosphere and have a global impact on climate : therefore, effusive basaltic volcanism on a large scale could alter climate (our group with Frédéric Fluteau and Anne-Lise Chenet and Steve Self with Thor Thordarson). Petrologic, volcanological, paleomagnetic, paleontological and geochronologic studies of the entire 3000m thick Deccan pile have been resumed (mainly our group, that of Self with Mike Widdowson and Anne Jay, and that of Gerta Keller). The result is that the thick lava pile actually erupted in a relatively small number of gigantic pulses (with mega-flows up to 10000 km^3 in volume having erupted in decades !). Field evidence has been given that flows could extend over almost 1000km, and paleontological and K-Ar dating now reveals a history of mainly two mega-pulses having occurred, one just prior to the KT the second somewhat afterwards explaining the long delay of recovery of species from the catastrophe. There is little doubt now that the KT catastrophe would have occurred even if the impact (which did have a significant additionnal effect) had not struck, and that the impact could not have generated a mass extinction if volcanism had not already been going on. Finally, global change during these periods of anomalous volcanism may provide interesting benchmarks for modelling of more current potential global change, and geologists be a major help to climate modelers.

Tracking the Kalahari Epeirogeny: from fission tracks and cosmogenic dating to molecular clocks.

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South-Central Africa's high Kalahari Plateau and its flanking mountain ranges that define a peripheral escarpment formed episodically over an extended period of ~200 million years, through tectonic processes different from those at convergent plate boundaries. We refer to this as the Kalahari Epeirogeny. Episodicity of substantial vertical motions at the end Mesozoic is established from the exhumation history of southern Africa, and stratigraphy of sediment accumulated around its margins. Subsequent Cenozoic motions are more subtle, ill-defined and poorly dated. The causes of the Kalahari uplift and associated exhumation of its lithosphere remains elusive. Feedback processes between the core, mantle, lithosphere and the fluid-envelope (exosphere), implicated as mechanistic causes, have in tandem affected climate, magnetic field changes, and not least, the evolution of biodiversity and landscapes. Here we focus on the need for more acurate dating techniques to pursue a robust interdisciplinary analysis of the Kalahari Epeirogeny and its geo-ecodynamics. Some of the dating may be best derived from genetic codes.

Following the ~50 myr break-up period of Gondwana (~120-170 Ma) a thickness of 2-7 km of rock, of which basalt was a major component, was eroded from the Kalahari Plateau over about 40 myrs. The clastic products of this erosion are preserved as accumulated Cretaceous sediments around its margins. Thermochronology, using mostly apatite fission track analyses (AFTA) along plateau-to-coast transects across the escarpments flanking both the Atlantic (west) and Indian Ocean (south) coasts provide similar, but not identical exhumation histories. Along the Atlantic coast AFTA on surface samples imply accelerated cooling (and denudation) during two episodes: late Jurassic to early Cretaceous (130-160 Ma), and in the mid Cretaceous (90-110 Ma). Between the escarpment and the coast, a total of ~ 4 km of bedrock was removed, whilst inland of this escarpment, vertical denudation removed less than 2 km. Along the south coast, and up to 600 km inland, AFTA on borehole samples shows that accelerated denudation occurred here in two Cretaceous episodes: between ~120-140 Ma, and between ~80-100 Ma. In this region, a total thickness of between ~4.5-6.5 km bedrock was removed: ~1-3 km during the early Cretaceous episode (at denudation rates ~200m/Ma), and ~2-4 km in the mid Cretaceous (denudation ~210 m/Ma), by which time, the southern escarpment, about 200 km inland, was in its near present day position.

Three striking observations stand out with respect to the possible origin of the Kalahari epeirogeny: (i) major epeirogenic uplift occurred during the Mesozoic and was episodic; (ii) regional-scale magmatism and basaltic underplating (Figure 1) closely match three episodes of uplift: *first* above the escarpment near the west coast (~140-160 Ma; overlapping with the Chon Aike-Tobifera LIP ~150, and mostly confined to South America), *second* along the south and west coast (120-140; overlapping with the Etendeka LIP, ~132 Ma, also mostly confined to South America). Both these events are probably associated with vast amounts of underplating along the passive Atlantic margins), and *third* flanking the sheared south coast margin of Africa (~ 90-100 Ma, overlapping with the Agulhas oceanic LIP). Surprisingly, any influence of uplift that might have accompanied the larger Karoo igneous province (~174-184 Ma) is not readily detected in Africa; (iii) the last two main regional episodes of accelerated denudation/sediment accumulation are near synchronous with two regional 'spikes' of kimberlite intrusions: >450 kimberlites at ~90 Ma, and >200 kimberlites at ~120 Ma (Figure 2).

How Mesozoic uplift can be reconciled against this regional punctuated epeirogenic history remains to be resolved. Southern Africa is presently underlain by an anomalous warm region in the lowermost ~1500 km of the mantle that may be linked to core to mantle heat loss. Nonetheless, this heat is not currently being transmitted to the relatively cool overlying upper mantle and the lithosphere directly above it, as it apparently did in the Mesozoic. One possibility is that this present warm region was inherited from a large Cretaceous thermo-chemical anomaly in the lower mantle created during long-lived subduction beneath Gondwana; and that related volatile/heat-induced density changes to the deep depleted Archean lithospheric mantle of southern Africa during Mesozoic kimberlite genesis and basaltic magmatism were sufficient to drive and sustain the uplift ('bottom-up' epeirogeny). A second possibility is that such magmatism/metasomatism was caused by tectonically-induced decompressional melting resulting from tangential forces, for example, through far-field collision processes between Africa and Europe, and/or final continental lithosphere decoupling between the Falkland plateau and southern Africa ('top-down' epeirogeny). Either way, substantial mantle-CO_2 was released into the ocean-atmosphere system during the epeirogeny, which may have contributed to global greenhouse warming by the mid-Cretaceous. However, because the CO_2 consumption rate associated with basalt weathering is about 8 times that of granite, any atmospheric CO_2 increase would have been offset against consumption during the rapid epeirogeny-induced regional erosion of the Karoo volcanic rocks. Whether the total CO_2 -budget was balanced in this way, or not, remains to be resolved. Nevertheless, it is possible that the epeirogeny and its feedbacks through atmospheric CO_2 -drawdown may have influenced the onset of long-term global cooling into the Cenozoic to a more significant degree than did the subsequent biological CO_2 pump initiated through opening of ocean gateways in the southern oceans such as the Drake Passage.

A general lack of Cenozoic apatite ages shows that major exhumation was over by the end of the Cretaceous. Vertical denudation decreased by more than an order of magnitude, removing less than 1 km thickness of rock over the following ~65 myrs (<15m/Ma). Erosion rates during the Cenozoic were thus substantially less. Preliminary results from cosmogenic dating shows that erosion rates today are almost an order of magnitude less still.

Resolving epeirogenic movements and their cause (s) throughout the Cenozoic, therefore, is more challenging because relative vertical movements and exhumation of the Kalahari Plateau are relatively low, as are off-shore sediment accumulation rates around southern Africa. This places onerous demands on established dating techniques. For example, AFTA is not generally able to resolve the subtle changes. The widespread terrestrial sediment cover (e.g. 'the Kalahari

Sands', the 'Namib', Tswang crater lake sediment) has been dated with variable success using widely different direct- and proxy- techniques (luminescence, radiocarbon dating, stable isotope analyses), in part because the sequence is condensed, not preserved, or not recorded in the first place. The lack of a universal stratigraphy of Kalahari sediments is a major deficiency, which obviates correlating the evolution of depocentres that extend from the Northern Cape to the Congo Basin (Figures 3 and 4). Moreover, high-resolution off-shore chemo- and seismic-stratigraphy remains difficult to correlate with the onshore deposits. Alternative methods must thus be explored.

It is widely appreciated that throughout the Cenozoic, Africa's bimodal topography has controlled Africa's river drainage basins and associated biotic evolution profoundly, as is well documented, for example, in first order biogeographical patterns of Afrotropical biodiversity. They are present in the composition of lowland and upland fauna and flora, and are especially evident in the distributions of fishes across the continent. Patterns associated with evolution of aquatic landforms feed back on tectonic controls over drainage evolution. The Kalahari Epeirogeny has accompanied, and in fact underpinned, radical rearrangements in drainage topology across and around the entire Kalahari Plateau. This link underlies a novel source of historical signals that provide insights into intricacies of the Kalahari Epeirogeny. They centre on what species tell us about landscape evolution, as revealed by dates of bio-evolutionary events, which are estimated using the theories and tools of population genetics, constrained by molecular clocks. Whilst such applications may at first appear unorthodox stances to solve what are established problems in the geology, the methods centre on quantifying genetic variation, within and among indicator species, in time and space. This genetic variation is structured into phylogeographic patterns that reflect on historical changes to landscapes.

Molecular clocks calibrate phylogeographic patterns, and can thus confer promising evidence to constrain more recent aspects of the Kalahari Epeirogeny. These insights especially apply to more recent patterns in both crustal and biotic evolution. The vertical dimension of genetic variation can be deciphered and read as a gene tree, in which divergence within gene trees reflects speciation events, caused when particular formative events changed the erosion surfaces or river drainage systems across the Kalahari Plateau. These genetic datasets present a hitherto unrecognized time-window. Applications of molecular genetic studies are developing into exciting partnerships between the earth and life sciences, aligned to decipher twinned narratives of Earth history. Evolutionary biologists and geochronologists are poised to combine methods and evidence obtained from gene trees (calibrated by molecular clocks) with those obtained from cosmogenic dating of the sediments/rock outcrops of habitats where these organisms speciated. These combined signals offer opportunities to obtain consilient resolution from both biotic and geomorphological signatures of landscape evolution and most importantly, they provide unique insights into deciphering causes of these interrelated evolutionary events.

Their relevance to research into the Kalahari Epeirogeny relates speciation of aquatic organisms to episodes of uplift (subsidence) that altered drainage patterns and thus their wetland habitats. Suites of speciation events followed on topological changes within and across river basins, which since Cretaceous times have been buffeted by dynamic drainage rearrangements. It is at the finer-scale that more subtle biogeographical signatures can tell not only biologists, but earth scientists, a great deal about where and when critical events changed the surfaces of the Kalahari Plateau. For example, interrogations of gene trees, represented in pairs of related aquatic species distributed across neighbouring wetlands, can reveal when they diverged, which points in turn to when formerly contiguous habitats were fragmented by river piracy or analogous events in drainage evolution. We term these biotic indicators of landscape evolution, as the extant survivors in modified landforms preserve the timings of formative events; where the signals are encrypted in their DNA. Comparisons of suites of such biotic indicators refine, and strengthen historical evidence to quantify when drainage systems were altered (Figure 3). Ongoing studies of these suites of biotic indicators centre on radical changes in the Zambezi and Upper Congo systems, whose rivers have drained the Kalahari Plateau througout the Cenozoic. Post-Miocene events in drainage evolution point to at least two major tectonic pulses that greatly expanded the exhorheic catchments of both the Zambezi and the Congo in the Pleistocene.

A recently quantified example reveals that recent speciation, in wetland-dwelling lechwe antelopes (*Kobus leche* complex), was driven by vicariance of Zambezian drainage systems in the Middle Pleistocene. The palaeo-drainage dynamics, which caused this speciation pulse in wetland biota, correlate with a pulse of volcanism in the Rukwa-Rungwe portion of the south (west) propegating East African Rift System (EARS). It was from here, on the northeast margin of the Kalahari plateau, that tectonic activity ramified southwest across the Kalahari plateau. This had subtle, yet profound impacts on the surface topography across High Africa, and significantly, foci of this activity are revealed where drainage topology was altered.

Analogous signals of relative sea level changes are preserved in fish species (e.g. the redfin barbs, a suite of Gondwana endemics) in the mountain streams of the southeastern Cape where they drain into the Indian Ocean. Plio-Pleistocene signals have been revealed in their genetic evolution, which reflect isolation of rivers formerly linked (and shared by these freshwater fish) on the coastal plain fringing the Indian Ocean. A complex history of interplay between eustatic sealevel changes and Kalahari uplift linked and finally isolated these rivers, whereafter endemic fishes evolved. The outstanding challenge is to quantify when these biotic indicators diverged against a molecular clock; as this will constrain when the coastal plain was finally inundated, isolating Cape mountain river systems across the margin of the Great Escarpment. The significant strength demonstrated by these methods is that one can isolate reliable geological events to anchor events of genetic divergence, and thus refine more precise mutation rates within gene trees, and in turn use these to determine uplift rates. This enhances the temporal resolution we can place on biotic indicators and the landscape scenario we are challenged to elucidate. Many of the published mutation rates are still vague - at best - but this combination of geology and genomics confers one very powerful way to tighten up resolution of evolutionary events. This consilient combination of geochronological and biotic (genomic) signals confers a greater resolution into earth history overall.

To resolve the cause and effect of the Kalahari epeiorogeny in greater detail will require more robust bridging between paleo mantle-dynamics and present day mantle-lithosphere tomography; better coupling with Gondwana break-up models; a more precise exhumation/climate history of the Kalahari region, the high fidelity stratigraphy preserved on and along its margins; and backtracking the molecular dating of speciation related to evolution of landforms (especially drainage); and then iteratively testing against 3-D geodynamic numerical models.

Figures

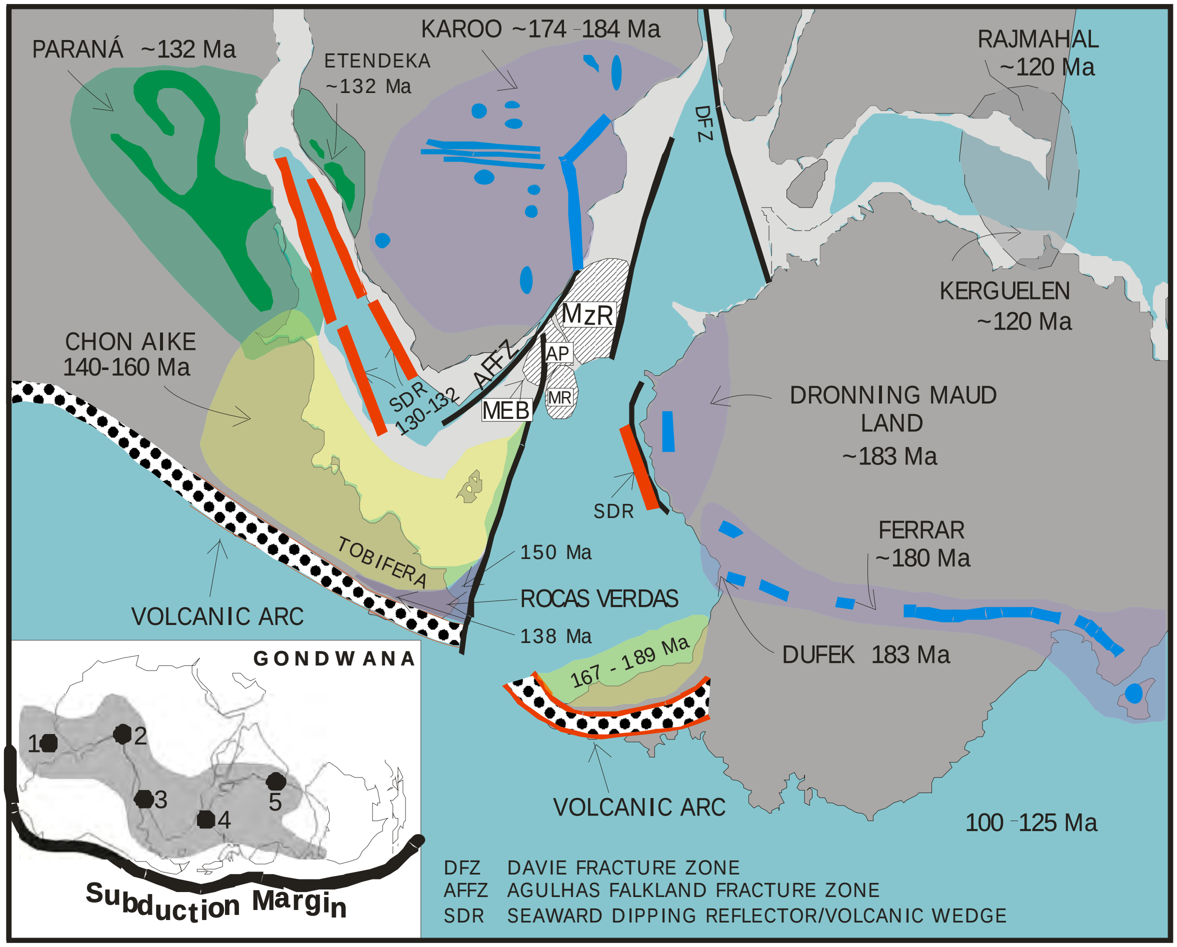

Figure 1. Large Magmatic Provinces (LIPs; in blue, yellow, green) that formed during the break-up of Gondwana. Note that around southern Africa the ages of the LIPs get younger in a clockwise direction from the Indian Ocean into the south-central Atlantic Ocean; and that there is a spatial relationship between the long-lived convergent margin (subduction beneath Gondwana of the Paleopacific plate) and mantle plume foci (1-5, inset) that are believed to be the cause of many Gondwana LIPs. Red lines/SDR = known Seaward Dipping Reflectors of Basaltic extrusives. In the south Atlantic, the lower continental crust beneath these SDR sections are underlain by thick sections of contemporaneous (underplated) basalt.

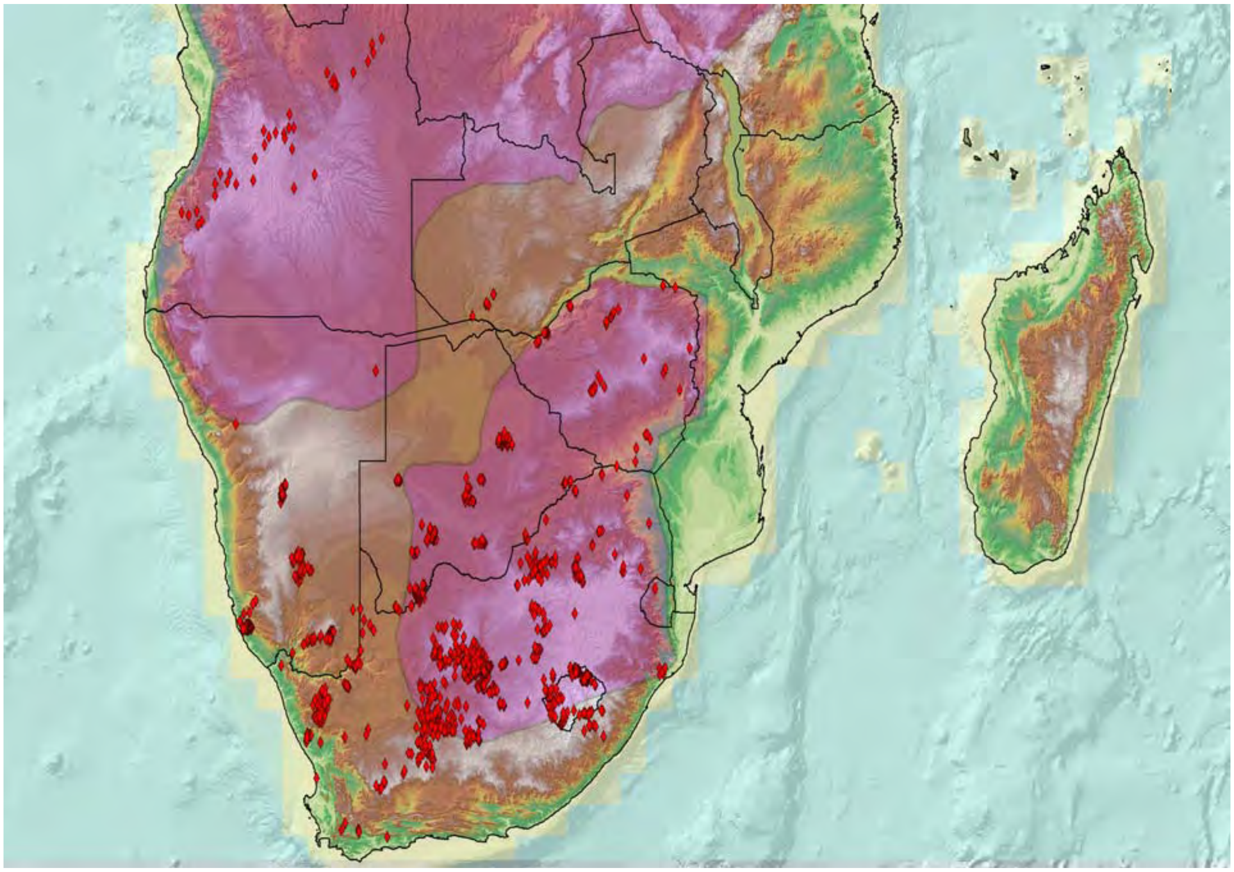

Figure 2. Regional distribution of kimberlites (red diamonds) across the Kalahari Plateau. For a more detailed age differentiated distribution of these kimberlites see figures 7a-c in Jelsma et al., 2004. Recent discovered kimberlites are not shown, nor are the known kimberlites of south-central Africa. Note the sublinear alignment of the kimberlites in Angola with the Walvis Ridge. Purple areas outline stable Precambrian regions: southernmost = Azanian Craton (> 2.5 Ga); northernmost = Central African Shield (> 1.0 Ga).

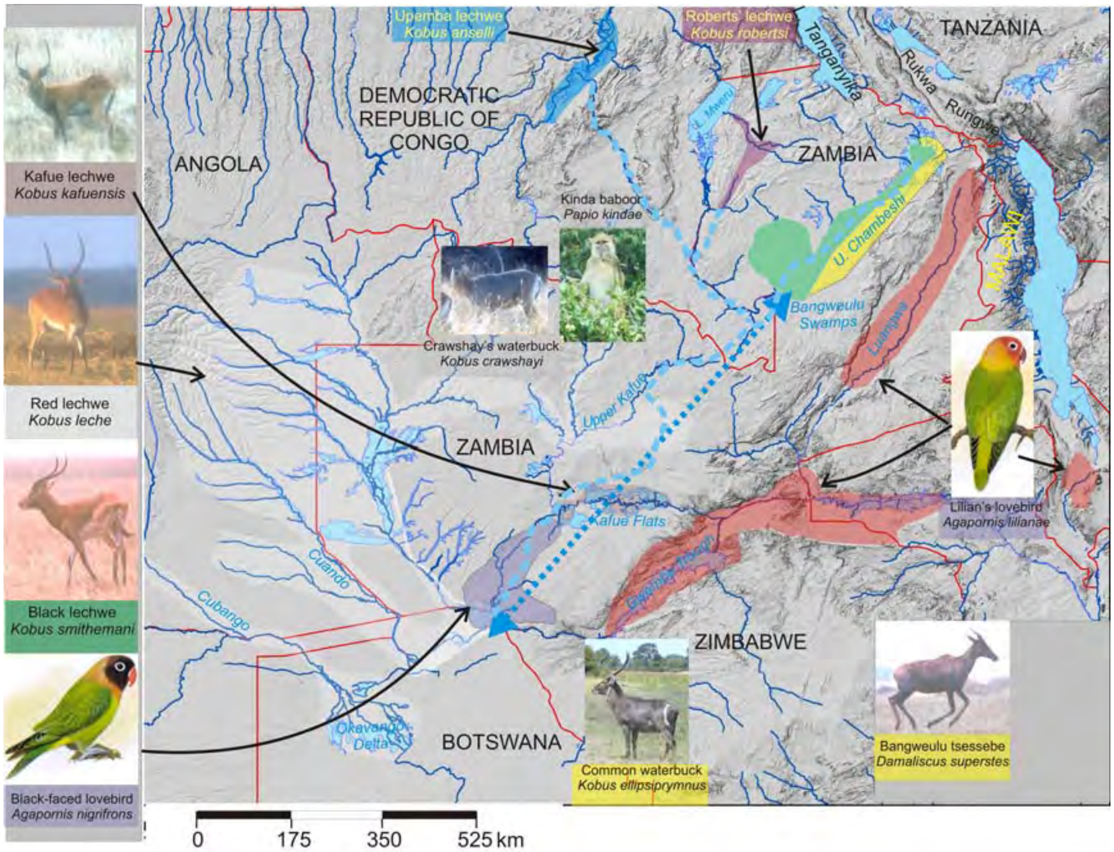

Figure 3. Examples of selected suites of biotic indicators to illustrate their fragmented distributions. Their speciation has been intimately coupled to the Late Cenozoic evolution of drainage systems across and around the Kalahari Plateau. This involved progressive break up of endorheic drainage systems around depocentres in a wetland archipelago (e.g. Figure 4). Consilient signals are reinforced further by speciation of terrestrial species, including cercopithicoid primates, birds and antelopes, isolated in savanna habitats northwest and southeast of the "Palaeo-Chambeshi axis" (dotted blue arrow) that reflects control by an extensive river system (dashed blue line). Their divergence reflects marked geographical control over speciation by a major river, the Palaeo-Chambeshi. Its Middle Pleistocene vicariance formed three isolated drainage systems: the Upper Chambeshi-Bangweulu (Ba), Upper Kafue (Ka) and Upper Zambezi-Okavango (Br, Ok Ma), as depicted in Figure 4. Suites of endemic species (left panel) have evolved in each of these river systems (exemplified by lechwe antelopes). Molecular clocks can constrain phylogeographic events, and thus date the geomorphic events underlying drainage evolution.

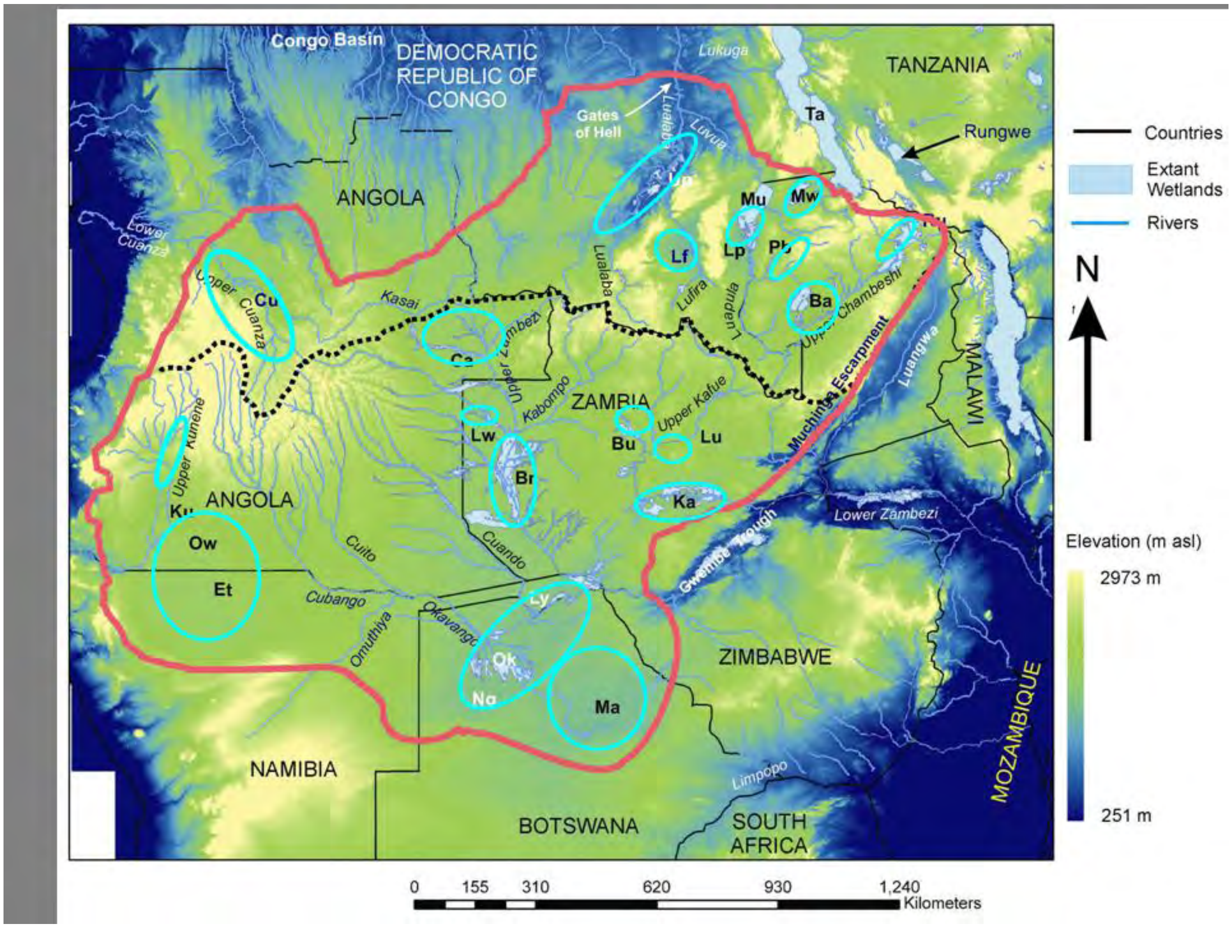

Figure 4. The wetland archipelago of south-central Africa. Each circle (pale blue) outlines the extent of a shallow depocentre on the Kalahari plateau, within the encompassing expanse of the Zambezian region. Many of these depocentres have shared historical links, which explains affinities among their aquatic fauna (see Fig. 3) that extend from near the Atlantic coast to Katanga (DRC) and catchments today flowing into Lake Tanganyika. Elucidation of the evolutionary histories of these species complexes is the subject of active genetic research.

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PALAEOGEOGEOGRAPHY OF AFRICA THROUGH MESO-CENOZOIC TIMES: A focus on the continental domain evolution

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In the frame of the INSU/CNRS programs « Reliefs » and « ECLIPSES », we developed paleogeographic database (ArcGIS) of the African plate (including Arabia) during Jurassic and Cretaceous times. The maps for Cenozoic are currently in progress. The main objective of this work is to focus on the continental domain in order to quantify the paleoelevations variations through this time interval.

- We first map the shoreline (and the type of shoreline: fluvial, wave or tidal-dominated), the bayline (and the lithology of the coastal plain: amount of evaporites or coals), the type of continental systems (lakes: deep vs. shallow, channel rivers: bedload vs. suspendedload rivers, alluvial fans). We also compile the paleocurrents data available on the fluvial deposits.
- We define the main river catchments and their divides, based on the paleocurrents data and the location of the river mouths on both lakes and seas. From this we define uncertainties on those catchments limits, their endoreic or exoreic nature, the characterization of the erosional, by-passing and depositional domains for each catchments (+ uncertainties on the limits between the different domains).
- We bring into coherence those first paleogeographic sketches with the boundary conditions defined by plate kinematics and magmatism (a magmatism database has also been compiled). From this we define the location of rift shoulders (if rifting), of highs of volcanic arcs (if subduction) or mountain belts (if accretion or collision), and of plateau associated with flood basalts (if plumes) or any other relief due to magmatic activity (alkaline small province, kimberlites…).
- The last step (in progress in collaboration with M. Simoes and J. Braun, see abstract this volume) is to build a first paleoelevation model based on the previous data and to test it on the base of a 3D model of erosion and transport at the African scale. The aim of this modelling is to predict (1) a thermal evolution of the lithosphere and (2) a sediment budget at the mouths of the different catchments. Those results have to fit with the thermochronological data (a fission track database has been compiled in collaboration with K. Gallagher, Geosciences-Rennes) and the measurement of the siliciclastic flux on the margins.

The Jurassic-Cretaceous evolution of the African plate is punctuated by some eustatic major flooding events: Middle Callovian (~162 Ma), Late Kimmeridgian (~152 Ma), Middle Aptian (~120 Ma), Late Cenomanian (~95 Ma), Maastrichtian (~70 Ma). A paleogeographic map as been compiled for each of those events and for some time intervals occurring between those eustatic floodings.

The main tectonic events responsible of relief creations were during:

- the Late Kimmeridgian-Early Tithonian (~155-150 Ma; Yemen-Somalian rift initiation, oceanic accretion in the Indian Sea),
- the intra Berriasian (145-140 Ma?) (birth of the central African rift system from Niger to Kenya, uplift of the Western African Craton, drowning of the Atlantic carbonate platforms and growth of Atlantic and Tethys deltas),
- the Austrian deformations (Barremian to Early Albian *e.g.* ~130-125 Ma: intraplate deformation with reaction of Pan-african structures in North Africa),

- the Late Albian to Cenomanian (~100-94 Ma: Ethiopia/Somalia uplift, tectonic relaxation elsewhere and continental onlap),
- the Turonian to Maastrichtian (~90-65 Ma) with a paroxysm at the Santonian/Campanian boundary (~84 Ma) main intraplate deformation of Africa, uplift of the South African Plateau in two times: Cenomanian eastward and Campanian westward: Kalahari epeirogeny of de Wit, *in press*).

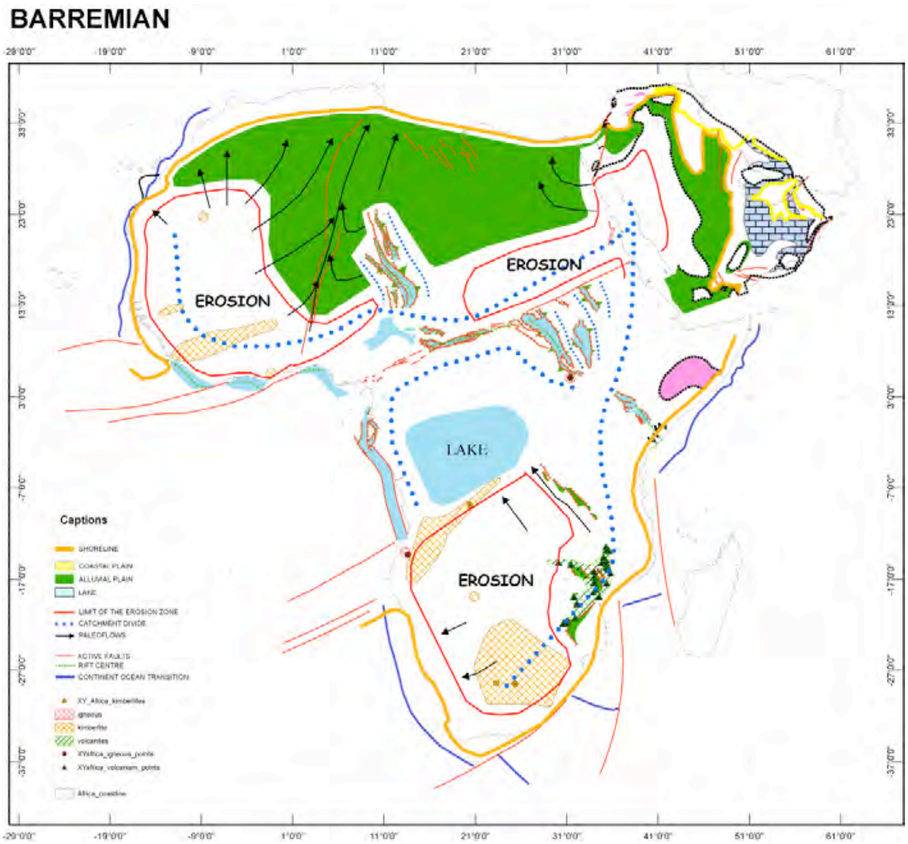

Figure 1: Example of new-style palaeogeographic maps focussing on the continental domain, with location of the main watersheds divides (dotted blue lines), of the erosional and depositional parts of the catchments and the different base-levels (lacustrine vs. marine).

The topography of Africa during Late Jurassic to Late Cretaceous is mainly controlled by a very long wavelength deformation showing a maximum in the middle part of North Africa (Mauritania to Sudan) and South Africa and a minimum along the Zaire "trough" corresponding to a large lake base-level. This long wavelength deformation is strongly modified during the Late Cretaceous time by the uplift of the Zaire "trough".
Consequently, the South African plateau turns out to be more or less a perennial structure since the Late Jurassic with a major uplift during Late Cretaceous, reactivated later during Oligocene times.

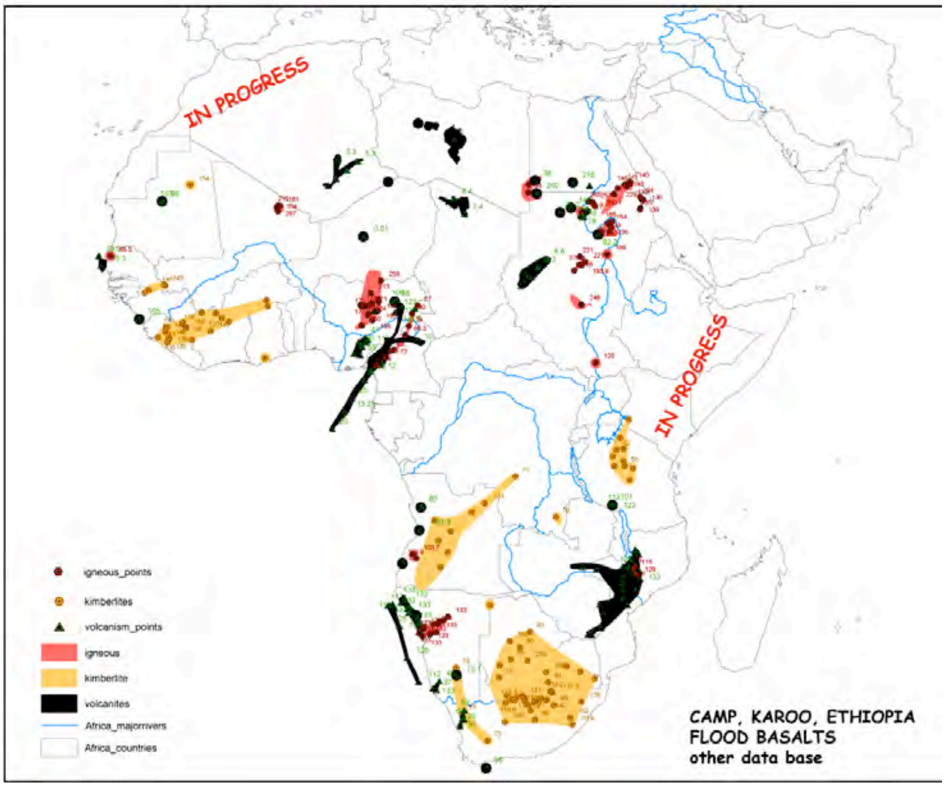

Figure 2: The magmatism database for the MesoCenozoic times. Each data have been digitized and associated with the petrology, the type of volcanism, the age and the type of dating techniques used.

A GEOCLIM SIMULATION OF CLIMATIC AND BIOGEOCHEMICAL CONSEQUENCES OF PANGEA BREAK UP

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Large fluctuations in continental configuration occur throughout the Mesozoic. While it has long been recognized that paleogeography may potentially influence atmospheric CO_2 via the continental silicate weathering feedback, no numerical simulations have been done, because of the lack of a spatially resolved climate-carbon model. GEOCLIM, a coupled numerical model of the climate and global biogeochemical cycles, is used to investigate the consequences of the Pangea break up. The climate module of the GEOCLIM model is the FOAM atmospheric general circulation model, allowing the calculation of the consumption of atmospheric CO_2 through continental silicate weathering with a spatial resolution of 7.5°long◊4.5°lat. Seven time slices have been simulated. We show that the break up of the Pangea supercontinent triggers an increase in continental runoff, resulting in enhanced atmospheric CO_2 consumption through silicate weathering. As a result, atmospheric CO_2 falls from values above 3000 ppmv during the Triassic, down to rather low levels during the Cretaceous (around 400 ppmv), resulting in a decrease in global mean annual continental temperatures from about 20°C to 10°C. Silicate weathering feedback and paleogeography both act to force the Earth system toward a dry and hot world reaching its optimum over the last 260 Ma during the Middle-Late Triassic. In the super continent case, given the persistent aridity, the model generates high CO_2 values to produce very warm continental temperatures. Conversely, in the fragmented case, the runoff becomes the most important contributor to the silicate weathering rate, hence, producing a CO_2 drawdown and a fall in continental temperatures. Finally, another unexpected outcome is the pronounced fluctuation in carbonate accumulation simulated by the model in response to the Pangea break up. These fluctuations are driven by changes in continental carbonate weathering flux. Accounting for the fluctuations in area available for carbonate platforms, the simulated ratio of carbonate deposition between neritic and deep sea environments is in better agreement with available data.

The sedimentary supply of African sedimentary basins over the last 250 Ma

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The African continent is bordered by passive margins and bears intracontinental basins preserving the terrigeneous sediment resulting from its erosion, and as such, recording the dynamics of its relief variation. The histories of the terrigeneous supply and denudation have most of the time been analyzed quite independently, mostly because, at geological time scale, the interpretation of sediment supply in terms of relief variation in the drainage area is far from straightforward. In that perspective, the understanding of sediment flux transfer from the drainage area to the sedimentary basin, at geological time scales (x10 Ma), is a critical step.

Our objective is to bring new constraints on the uplift and erosion of the African continent over the last 250 Ma from the perspective of the stratigraphic architecture of its sedimentary basins. The novel aspect of our approach is to integrate the evolution of both the domains in erosion and in sedimentation (*i.e.* from the drainage divide of the domain in erosion down to the most distal deposits over the oceanic crust; Figure 1), and to review published data to quantify the terrigeneous supply eroded in the drainage area and preserved in the basins. One objective is to evaluate the conditions under which this simple approach, based on already published data, can be used to infer continental relief variations, the sedimentary archives of the domain in erosion being by definition scarce and denudation evaluation by thermochronology usually relying on hypotheses on past heat flows.

We quantify the siliciclastic sedimentary volumes preserved in African basins correcting from porosity and *in-situ* (e.g. carbonate) production, with a particular attention to the determination of uncertainties resulting from parameters such as: velocity laws used to depth conversion of TWT data, biostratigraphic used for calibration in absolute ages, lithology assumed for porosity removal. We use three approaches with complementary spatial and temporal resolutions.

(1) When data are available (*e.g* along the South African and Namibian Atlantic margins), we determine the long-term signal of sedimentary supply (x10 Ma) from 3D mass balance calculations comparing sedimentary volumes deduced from offshore isopach maps (Emery *et al.,* 1975; Dingle *et al.,* 1983) on one hand and erosion volumes deduced from the present day geometry of geomorphic markers (Partidge and Maud, 1987) and thermochronology data (Gallagher and Brown, 1999ab) on the other hand (Figure 2). We show that our approach provide a good estimation of the long-term denudation of the drainage basins.

(2) For several sedimentary basins, only isopach maps are available, we use a similar approach to quantify the associated sedimentary volumes in the Kalahari and Zaire depressions, the Limpopo system and the north African basins (Morocco, Algeria, Tunisia and Lybia). Some basins have already been studied in that perspective (Outeniqua: Tinker, 2005; Zambezi: Walford *et al.,* 2005).

(3) 3D dataset are not always available and allow most of the time only a long-term description of the sedimentary supply. We therefore develop a GIS database of 2D regional cross-sections across the major sedimentary basins (Figure 3) established from published seismic lines. We homogenise the sections in spatial and temporal scale and then extrapolate them down to the most distal part of the basin so that geometries of our sedimentary wedges are not restricted to the platform domain (Figure 4), this, taking into account several hypotheses. On each cross-section, we then measure the 2D area of each stratigraphic interval (x1 Ma) and, in doing so, determine the average sedimentation "areas" and rates. We then determine the spatial extension of the basins for each time increment (Figure 4) and use it to extrapolate average sedimentation "areas" and rate into sedimentation volumes (Figure 5).

These results are then integrated with the set of 15 paleogeographic maps of Guillocheau *et al.* (this volume) and sedimentological analyses in key areas to discuss their implications in terms of

(i) the evolution at geological time scale of the major African drainage basins feeding these margins and their stratigraphic state,

(ii) the associated fluvial, deltaic and turbiditic systems, and

(iii) the evolution of the continental relief they develop onto.

Finally, these results are used to calibrate the TOPOAFRICA modelling tool (see Simoes *et al.,* this volume).

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FIGURES.

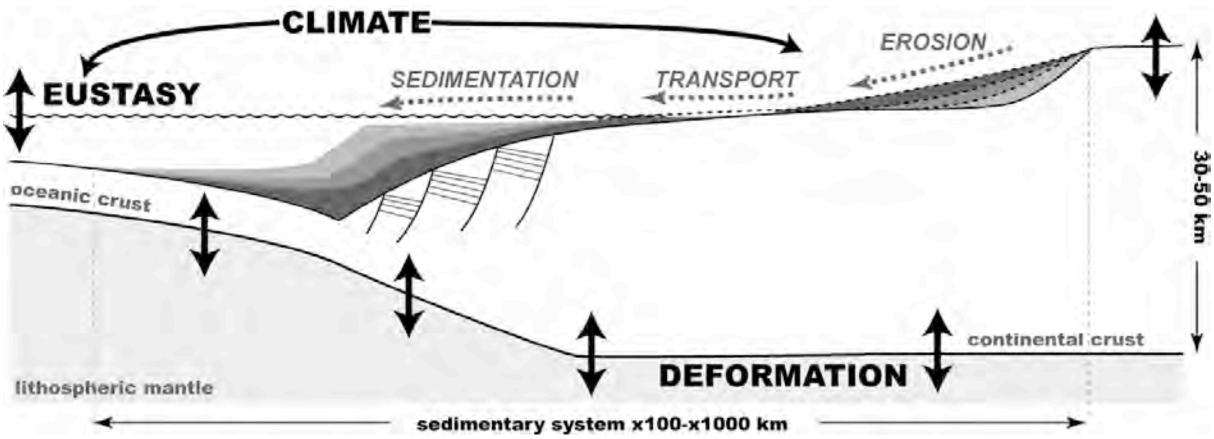

Figure 1: Sketch of a margin sedimentary system defined from the drainage divide down to the distal most deposits onto the oceanic crust, that is to say including both the areas durably in erosion and in sedimentation. Parameters influencing the evolution of the system are shown: climate and deformation.

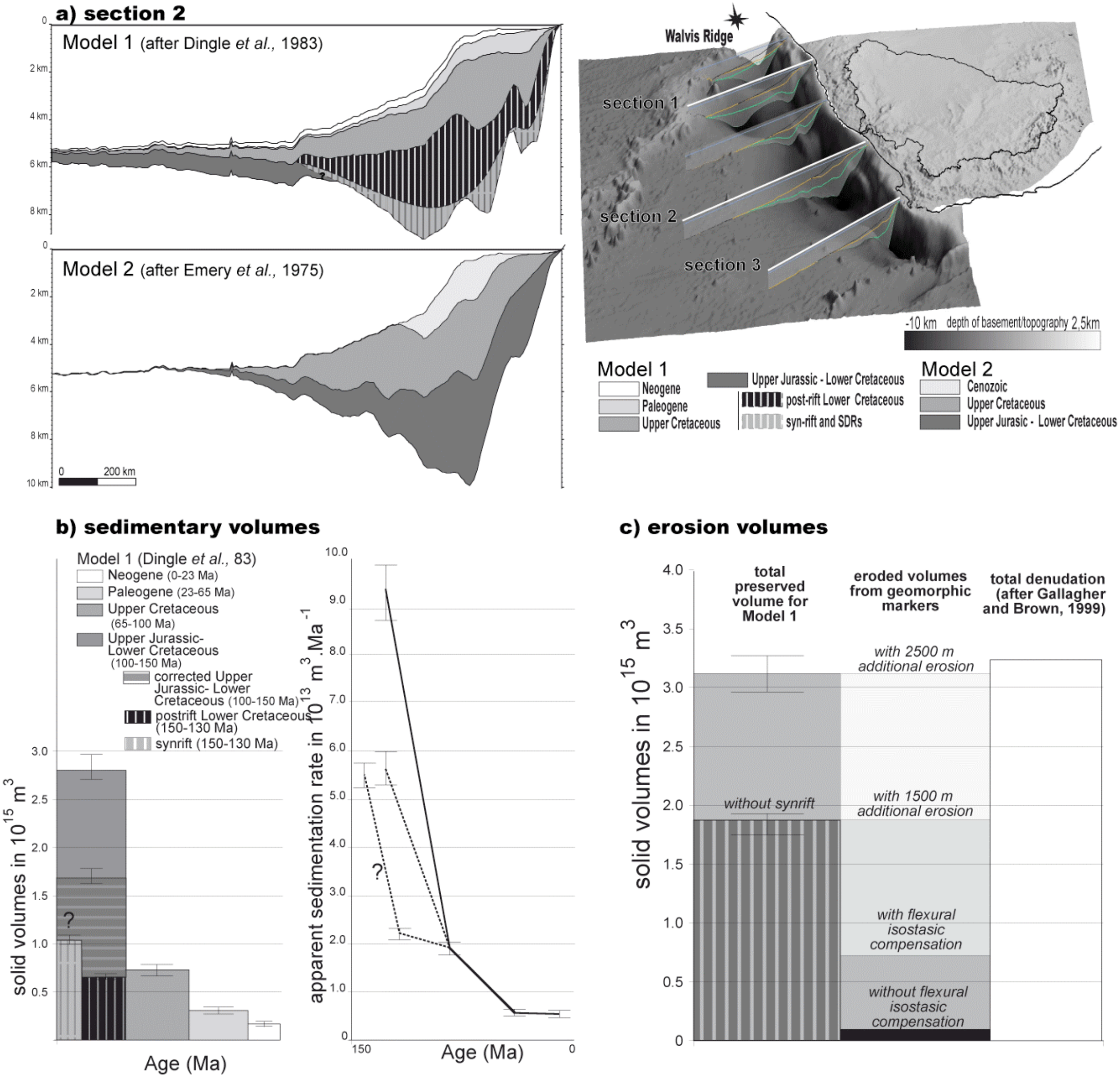

Figure: (a) Cross-sections trough the reconstructed 3D geometry of the sedimentary wedge along the Namibian and South African margin for Model 1 and 2 deduced from isopach maps published by Dingle *et al*. (1983) and Emery *et al*. (1975) respectively. (b) Incremental solid volumes (columns) and incremental sedimentation rates (thick line) measured for Model 1 (Dingle *et al.,* 1983), Estimated syn-rift and post-rift volumes are shown in dashed column (volumes) and dashed black line (rates). Uncertainties due to porosity removal are shown. Note the scale in 10^{15} m^3 for solid volumes and in 10^{13} m^3Ma^{-1} for apparent sedimentation or denudation rates. (c) Comparison of total preserved solid volumes for Model 1, total eroded volumes based on Partridge and Maud (1987) and denudation deduced from thermochronology (Gallagher and Brown, 1999). For Model 1, estimation without syn-rift is shown in dashed column (volumes) as well as uncertainties due to porosity removal are shown for Model 1. For eroded volumes estimation without flexural isostasy is shown in black, with flexural isostasy is shown in medium grey and with additional 1500m and 2500m erosion above the AS in light grey.

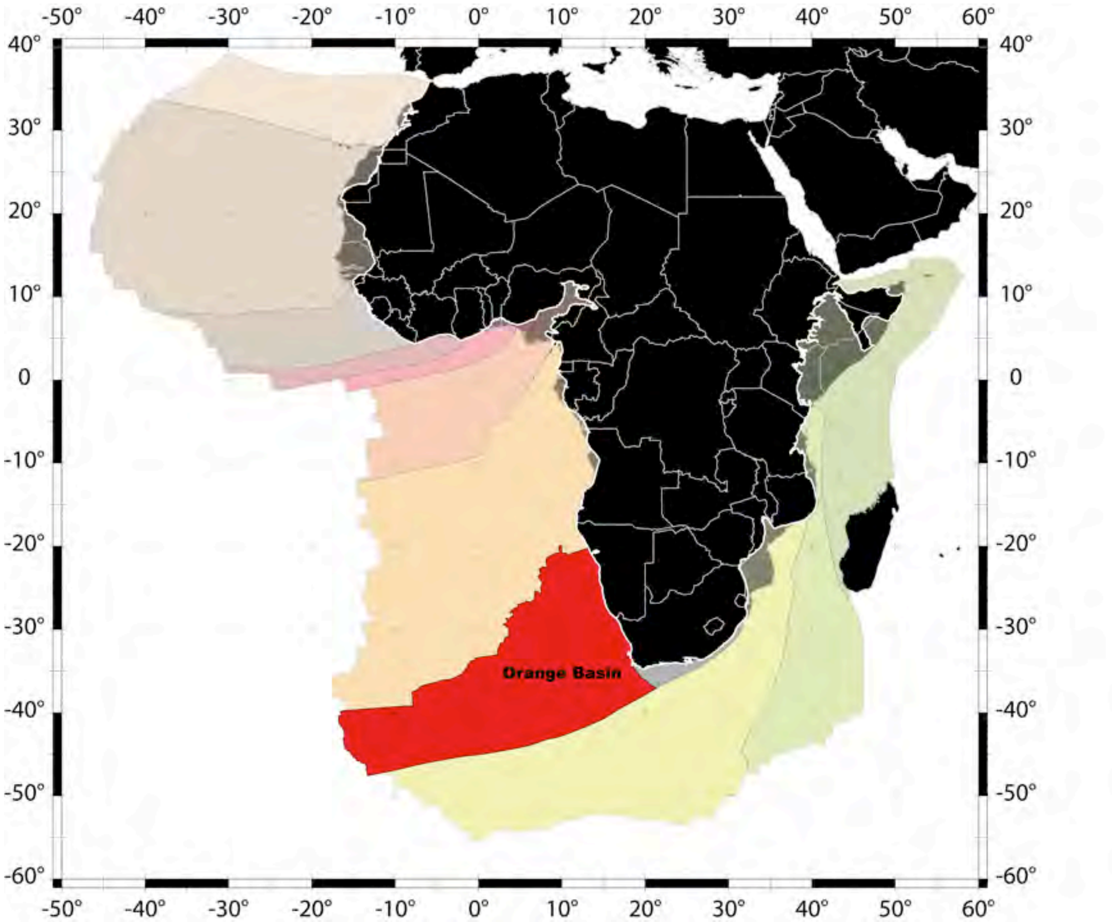

Figure 3: Map of the sedimentary basins used for the quantification of sedimentary supply in 2D. Measurement areas range from the upslope onshore outcrop limit of Meso-Cenozoic basins (white line) down to the mid-oceanic ridge. Results shown in Figures 4 and 5 are for the Orange basin (red).

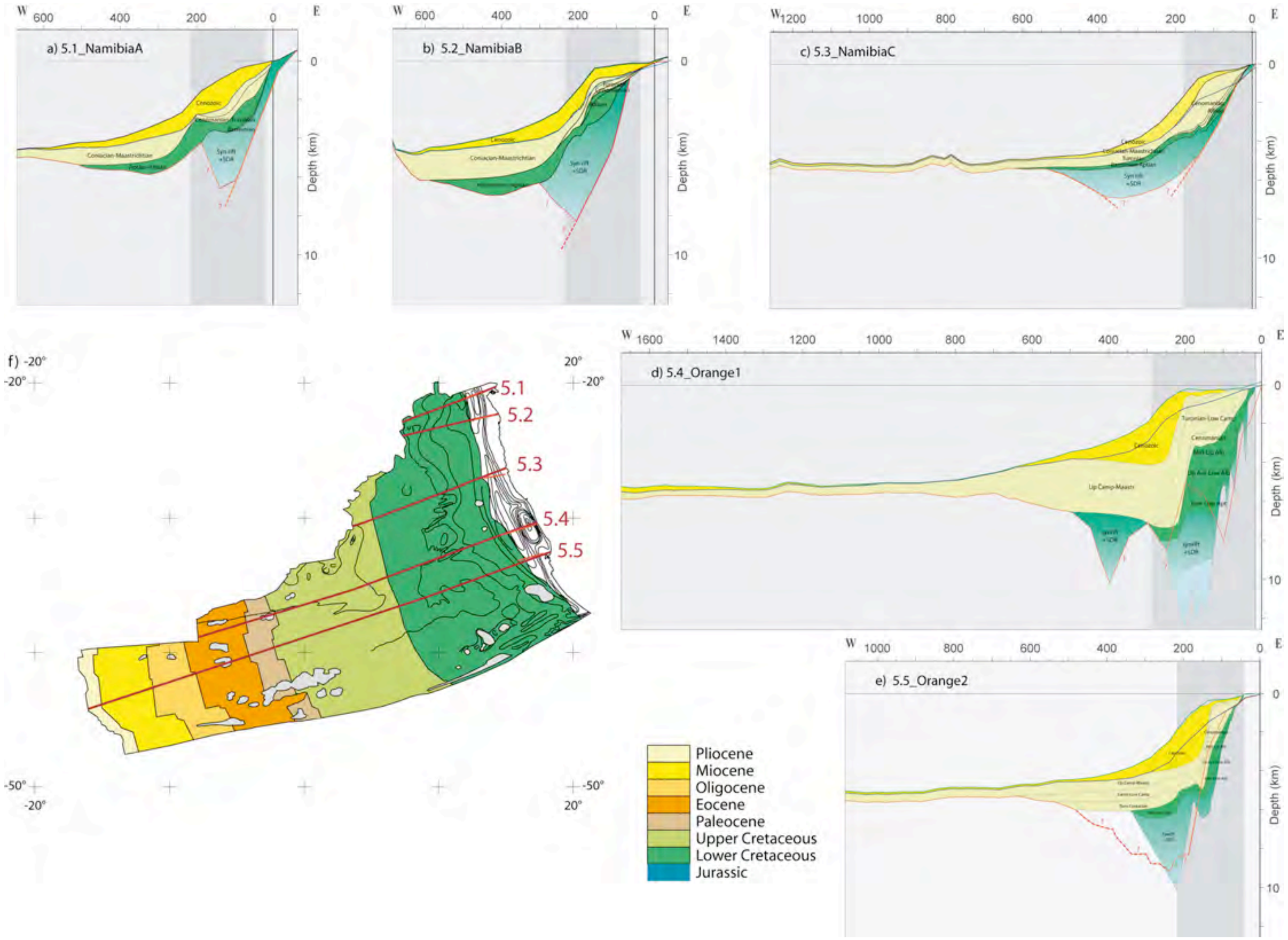

Figure 4: (a to e) Cross sections used for the measurement of sedimentation rates and volumes of the Orange Basin shown in Figure 5. See location in (f). Published cross-sections (after Brown *et al*., 1995; Aizawa *et al.*, 2000) cover the dark grey area on each section from which we extrapolated the geometry of the sedimentary wedge down to the oceanic ridge. (f) Map view of the extensions of the sedimentary basin during the Meso-Cenozoic determined from the age of the oceanic crust and the geometry of the sedimentary wedge.

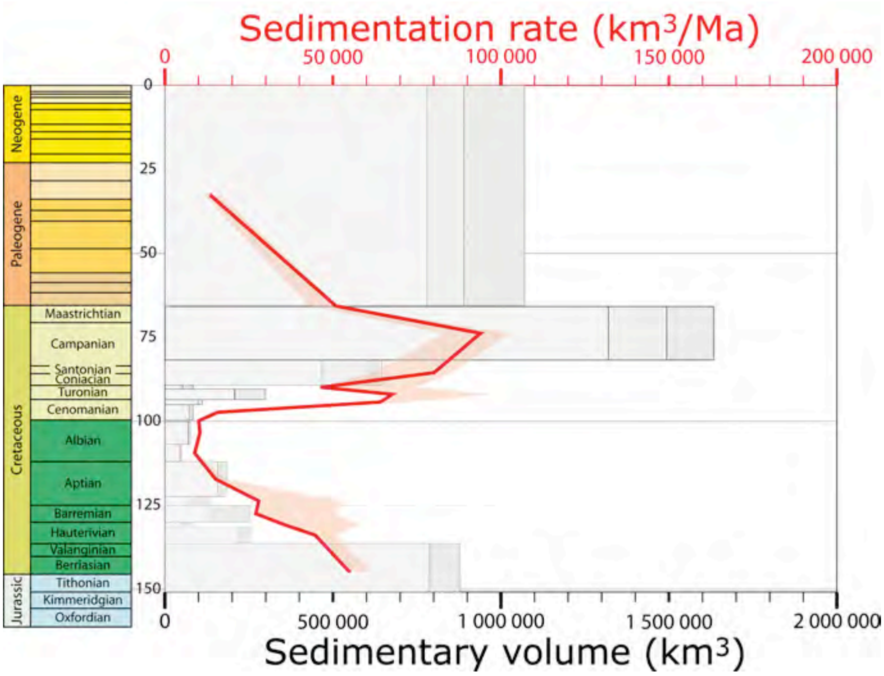

Figure 5: Averaged sedimentation rates and sedimentary volumes determined from the 5 cross-sections of the Orange basins.

THE TECTONICS AND GEOMORPHOLOGY OF AFRICA: AN OVERVIEW

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ABSTRACT

The African continent carries the legacy of many old geological events. The northern margin of the continent was first created from the late Permian onwards by the opening of the Neotethys seaway. At much the same time compression along the southern margin initiated the rise of the Cape Fold Mountains.

Rifting and continental separation along the east and west coasts of Africa were frequently preceded by volcanism. The combination of thermal effects and magmatic underplating created a high “rim bulge”in many areas. The highest post-rifting hinterlands coincided broadly with the area occupied by the African Superswell, which defines “High Africa” in the south and east as opposed to “Low Africa” to the north and west. Superimposed upon these broad divisions are a series of “basins” and “swells” which first came into being during the Neoproterozoic Pan-African-Brazilian orogeny. Episodic reactivation of the swells during the Cenozoic served to maintain the elevation of these features throughout most of the existence of Africa as a continent.

The tectonic history of Africa during Cretaceous and Cenozoic times was characterized by long periods of extensional stress as the other Gondwana continents drifted away from it. These were punctuated by relatively short intervals during which compressive stress regimes were (at least locally) dominant. It was during these periods of crustal shortening that the

major structural features of the Late Cretaceous and Cenozoic were superimposed upon the Gondwana mosaic of stable cratons and intervening Pan-African orogenic belts.

The first collision between the African-Arabian and Eurasian plates gave rise to a Santonian rifting event driven by plate boundary forces. A second major compressional event of continental extent dates to the Late Eocene and corresponded with renewed collision along the north of the continent. This caused Africa to come almost completely to rest with respect to the underlying mantle-plume system and other deep-seated anomalies, and initiated a wholly new stress regime across the continent. It was about this time that the African Plate began to suffer its first major disruption since its isolation by Gondwana rifting, with the commencement of the large-scale interior rifting that later gave rise to the East African Rift System.

The history of denudation across the continent, and the development of associated marine sequences on the newly-formed continental shelves, began with a prolonged period of erosion following the creation of the margins by Cretaceous rifting. Offshore loading by the resulting sediment sequences further uplifted hinterlands elevated by thermal events. This created the Great Escarpment, which is a major morphological feature of much of Africa. Its present position inland of the coast reflects the episodic recession of this feature during the Cretaceous and Cenozoic. By the end of the Cretaceous the coalescing surfaces produced by extended post-rifting erosion occupied much of the landscape of southern, western and eastern Africa.

In North Africa landscape development followed another pattern. Here large continental basins, formed during and after rifting, became hosts to deep sequences of terrigenous sediments; there followed the invasion of the North African platform by the sea in Cenomanian times. Despite local uplift and basin inversion during the Santonian tectonic event, much of North Africa remained occupied by the shallow seas. It was only during the movements caused by the late Eocene compressional event that the sea receded and basin sedimentation resumed. Late rejuvenation of inter-basinal swells in this area was driven by the development of a number of important volcanic provinces north of the equator.

Abundant evidence exists for Miocene tectonism on a sub-continental to regional scale. Early Miocene uplift in Angola is, for example, well documented in the marine succession of the Kwanza Basin, and similar evidence points to elevation of the Congo margin in

Burdigalian and, later, Tortonian times. Thermo-chronological studies confirm the occurrence of about 500 m of Miocene uplift in the coastal basin of Gabon and Angola. Increased sediment inputs are similarly evident off the mouths of rivers draining the south-eastern margin of the continent, where Late Miocene marine sediments are found at elevations of up to 400 m. The diachronous nature of these Miocene movements was expressed in the creation of discrete scarps separating areas of partial planation. These, together with yet higher-lying remnants of the widely developed end-Cretaceous surface, give to Africa the unique multi-storeyed morphology and the anomalous hypsography that characterizes large areas of the continent. The occurrence within the same landscape of surfaces of different ages is, as was argued from the mid-twentieth century onwards, possible only if the dominant mode of landscape evolution is the formation and lateral recession of escarpments, rather than surface down-wearing. There is a very substantial body of data from within the landscapes themselves that proclaims scarp recession to have dominated landscape evolution in Africa since the continent first came into existence.

Scales of Transient Convective Support Beneath Africa

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Abstract: It is now accepted that a significant proportion of present-day African topography is dynamically maintained by mantle convection. Beneath sub-equatorial Africa, there is convincing evidence for a gigantic slow velocity anomaly within the lower mantle which is inferred to be a thermochemical superplume. Dynamical calculations have shown that this superplume can account in general terms for the surface elevation and uplift rate of southern Africa. However, there is a pressing need for better resolved measurements of the spatial and temporal variation of Cenozoic uplift. Here, we constrain the spatial and temporal pattern of uplift across the northern edge of the putative superplume by analyzing stratal geometries and stacking velocities of Neogene sedimentary rocks. These marine deposits are imaged on a dense grid of seismic reflection profiles which traverse the West African coastal shelf. Inverse modeling of stacking velocity profiles demonstrates that there have been two discrete phases of uplift. A post-Pliocene uplift event increases from zero to $\sim$ 500 m over a distance of $\sim$ 1000 km, in close agreement with the variation of dynamic topography estimated from long-wavelength gravity anomalies and with the results of higher mode surface wave tomography. An earlier phase of uplift occurred in Middle Oligocene times ($\sim$ 30 Ma). This phase has an amplitude of up to 1 km and, crucially, its spatial distribution does not correlate with the observed pattern of present-day dynamical support. We infer that this earlier phase of uplift records initiation of a relatively static superplume whereas the post-Pliocene phase records vertical motions associated with upper mantle convection which varies on timescales of several million years. Our results support the existence of two-layered mantle convection beneath Africa.

Ever since *Holmes* (1944) described the long-wavelength topography of Africa in terms of basins and swells, there has been considerable interest in exploring how the spatial and temporal variation of relief and drainage are modulated by convective circulation of the mantle. Three interlocking sets of observations can be used to tackle this problem. First, the dynamic (i.e. convective) support of a region can be estimated by carefully removing the isostatic effects of crustal and lithospheric structure. *Nyblade and Robinson* (1994) showed that a large region with an average dynamic topography of 500 m encompasses much of sub-equatorial Africa (Figure 1). Secondly, seismic tomographic methods help to constrain sub-lithospheric velocity anomalies which can be used as proxies for the pattern of temperature variations associated with convective circulation. Within the lower mantle beneath southern Africa, there is excellent evidence for a giant low velocity seismic anomaly centered on $25°$ S, $25°$ W. This irregularly shaped feature is thought to be predominantly a thermal anomaly, although the sharpness of its southwestern edge suggests that compositional variation plays a moderating role. Thirdly, long wavelength (> 1000 km) free-air gravity anomalies, which are mainly generated by density variations within the upper mantle, help to gauge the amplitude and wavelength of convectively supported topography. Large domes of dynamic uplift occur around the southwest coast of Africa within a region encompassed by the superplume (Figure 1). Dynamic uplift of ~ 1 km is also associated with hotspot features in North Africa (e.g. Hoggar, Tibesti and Afar volcanic regions).

Despite important advances in seismic imaging of the sub-lithospheric mantle beneath the African plate, our understanding of the temporal and spatial variation of sub-African convective circulation remains sketchy. When did the superplume appear? How has the superplume evolved through time and space? Does two-layered mantle convection occur? If so, what is the temporal and spatial relationship between upper and lower mantle convection? We can begin to address these general questions in two ways. The first approach is essentially theoretical and exploits the relationship between the density structure of the superplume and the dynamic topography which it generates at the Earth's surface (*Gurnis et al.*, 2000; *Lithgow-Bertelloni and Silver*, 1998). Results are highly dependent upon the assumed viscosity structure of the mantle but they do suggest that the superplume maintains the long-wavelength topography of sub-equatorial Africa.

The second approach is predicated on fact that temporal and spatial evolution of convective circulation should have important effect on the geomorphological history of Africa. It is instructive to examine Africa as a whole and to compare it with other continents. The relationship between gravity and topography in the frequency domain is an important guide and shows that long-wavelength gravity anomalies result from mantle convection. On most continents, however, much of the topography results from crustal thickening and so is not a direct expression of mantle convection. Africa is the most obvious exception where many important geological features must be dynamically supported by mantle convection (Figure 1). The relationship between gravity, topography and drainage imply that patterns of uplift and subsidence change on timescales of millions of years. Offshore, especially in river deltas, there is excellent evidence for temporal variation in the solid flux of clastic sediment (*Al-Hajri*, 2006; *Walford*, 2003). We suggest that the spatial and temporal distribution of basin subsidence and deposition have been influenced by vertical motions associated with time-dependent convection.

The main problem is that it is very difficult to measure the spatial and temporal variation of uplift on length scales of 10^1–10^3 km and on time scales of 10^0–10^1 Ma. An important exception is the coastal shelf where stratal geometries are likely to be especially sensitive to small vertical motions. We have chosen to analyze the West African coastline for two general reasons. First, this coastline straddles the northern edge of the superplume. Secondly, the coastline intersects a series of long-wavelength gravity highs and lows whose origins are probably convective. Our principal interest is in determining the amplitude and wavelength of Cenozoic uplift events across these important boundaries. An important advantage is that Cenozoic strata along this margin are structurally simple since they represent post-rift subsidence which occurred after continental rifting between Africa and South America.

The detailed stratigraphy of the margin has been imaged on a regional seismic reflection survey generously provided by WesternGeco Ltd. One profile is shown in Figure 2a and b, which illustrates the typical stratal geometry observed along the length of this margin. We are primarily interested in the development of the two unconformities which are clearly visible on Figure 2a. Careful examination shows that truncation of older strata against the Oligocene unconformity decreases seaward so that Paleogene and Neogene strata are conformable west of CDP 2500. This geometry suggests that uplift and erosion was caused by westward tilting of West Africa. This Oligocene unconformity can be traced around much of sub-equatorial Africa. The amount of denudation (0.5–1 km) means that it is less likely that this unconformity was generated by eustatic sea-level fall. A younger unconformity occurs where Neogene strata are truncated against the seabed. Close examination shows that the truncated strata mainly consist of foreset deltaic deposits which prograde westward. This unconformity also dies out seaward so that no truncation occurred west of CDP 3000. Landward of the shelf break, Neogene foresets are progressively truncated until the seabed unconformity merges with the Oligocene unconformity at CDP 1500. The youngest truncated deltaic sediments are Pliocene in age.

Walford and White (2005) showed that root-mean squared stacking velocities increase systematically across the continental margin. This gradual increase is correlated with the extent

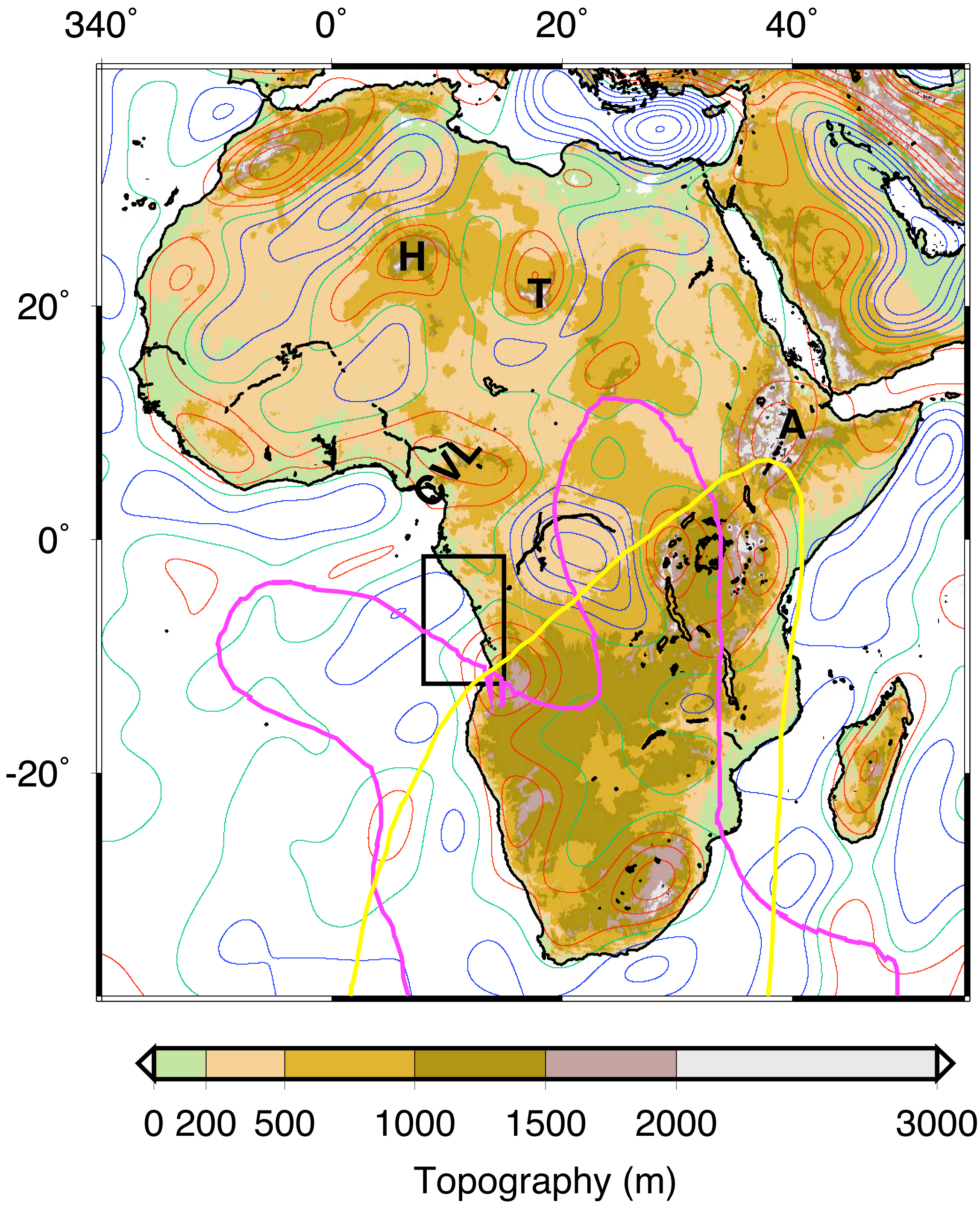

Figure 1: Topographic map of Africa overlain by long wavelength gravity anomalies from GRACE GCM02S database. Note strong positive correlation between topography and gravity. Red, green and blue contours = positive, zero and negative free-air gravity anomalies plotted every 10 mgal (filtered with central frequency of 0.00125 km^{-1} and bandwidth of 0.000167 km^{-1}). Black rectangle = study area; pink line = surface projection of S wave seismic anomaly with shear velocity perturbation of -0.7 to -1.4% located 2100 km beneath sub-equatorial Africa (from S-wave tomography model S20RTS); yellow line = African superswell as delineated by Nyblade & Robinson (1994); **CVL** = Cameroon Volcanic Line; **A** = Afar Region; **T** = Tibesti Massif; **H**= Hoggar Massif.

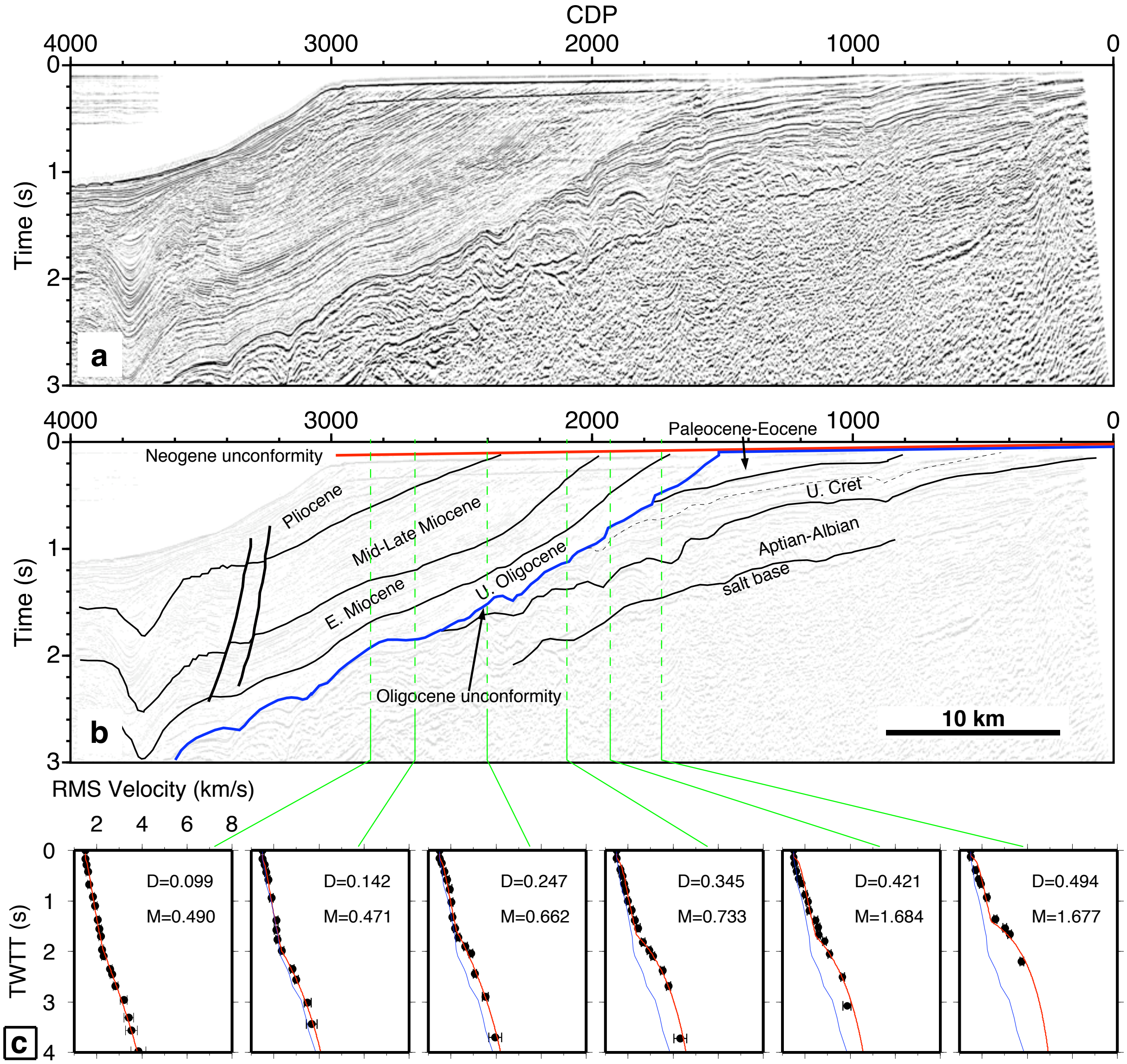

Figure 2: Seismic reflection Line A, which crosses Angolan margin (see Figure 3 for location). (a) Uninterpreted section. Note pronounced sea-bed unconformity between CDPs 1600 and 3000, older deep unconformity indicated by major change in reflectivity (e.g. at CDP 2000, 1 second), minor normal faulting at left-hand edge, and salt diapirism beneath deep unconformity. Seismic data generously provided by WesternGeco Ltd. (b) Interpreted section where strata are calibrated by regional well-log information. Red line = sea-bed unconformity where Upper Cretaceous-Neogene strata are truncated; blue line = deep unconformity where Upper Cretaceous-Paleogene strata are truncated by Oligocene strata. (c) Representative root mean square (rms) velocity profiles inverted as function of denudation. Solid black circles = observed rms velocity picks; horizontal error bars = uncertainties in velocity picks estimated from semblance calculations; red lines = best-fitting rms velocity calculated by varying denudation at both unconformities (initial porosity, ϕ_0 = 0.9, compaction decay length, λ = 2 km and matrix velocity, V_{ma} = 6 km s^{-1}); blue lines = calculated rms velocity profile for left-hand panel where $D \sim 0$ km. Each panel shows value of denudation at sea-bed unconformity and residual misfit. Note changing pattern of rms velocity toward coast.

of the sea-bed unconformity which suggests that it is caused by overcompaction of sediments. Overcompaction is, in turn, generated by regional uplift and denudation. *Walford and White* (2005) describe an inverse model which calculates the magnitude of denudation from stacking velocity profiles by minimizing the misfit between observed and calculated velocity profiles. They assume that the relationship between velocity and porosity is given by

$$\frac{1}{V} = \frac{\phi}{V_{fl}} + \frac{(1-\phi)}{V_{ma}} \tag{1}$$

where V_{fl} and V_{ma} are the velocities of the pore fluid (1.5 kms^{-1}) and rock matrix (6 kms^{-1}), respectively. The variation of porosity with depth, $\phi(z)$, is assumed to be

$$\phi = \phi_{\circ} \exp[-(z - wd + D)/\lambda] \tag{2}$$

Where $\phi_{\circ}$ is initial porosity, wd is water depth, D is denudation and λ is porosity decay constant. We model root-mean squared velocities, V_{rms}, directly and so Equations (1 & 2) must be recast into V_{rms} as a function of two-way travel time by using

$$t = 2\int_0^z \frac{dz}{V_{int}(z)} \tag{3}$$

and

$$V_{rms}^2 = \frac{\int_0^t V_{int}(t)^2 dt}{t} \tag{4}$$

where V_{int} is the interval velocity. By modifying the parameters, D, λ, $\phi_{\circ}$ and V_{ma}, the inversion routine finds the minimum of the misfit function using a conjugate gradient search algorithm (see *Walford and White* (2005) for further details). We have applied this simple method for estimating denudation to the West African margin (Figures 2 & 3). On Line A, Aptian-Eocene reflections are truncated at the sea bed landward of the surface intersection of Oligocene unconformity at CDP 1630. These strata are also truncated by the sub-surface Oligocene unconformity by up to 1.8 s TWTT. At the landward edge of this line, Upper Cretaceous and Paleocene sediments are excised. The parallel nature of the reflections indicates that 0.6 s are missing (i.e. 0.09 km, assuming a sediment velocity of 3 km s^{-1}). Neogene reflections seaward of CDP 1630 are truncated at the sea bed but it is difficult to estimate the amount of denudation from stratal geometries alone. Inverse modelling of stacking velocity profiles shows that post-Pliocene denudation increases from 99 m at the shelf break to 494 m at the middle of the shelf. This landward increase in denudation is supported by the truncation angle of the Neogene reflections with a steeper truncation at CDP 1880 compared with CDP 3000.

We have extended our analysis to the grid of seismic reflection lines shown in Figure 3

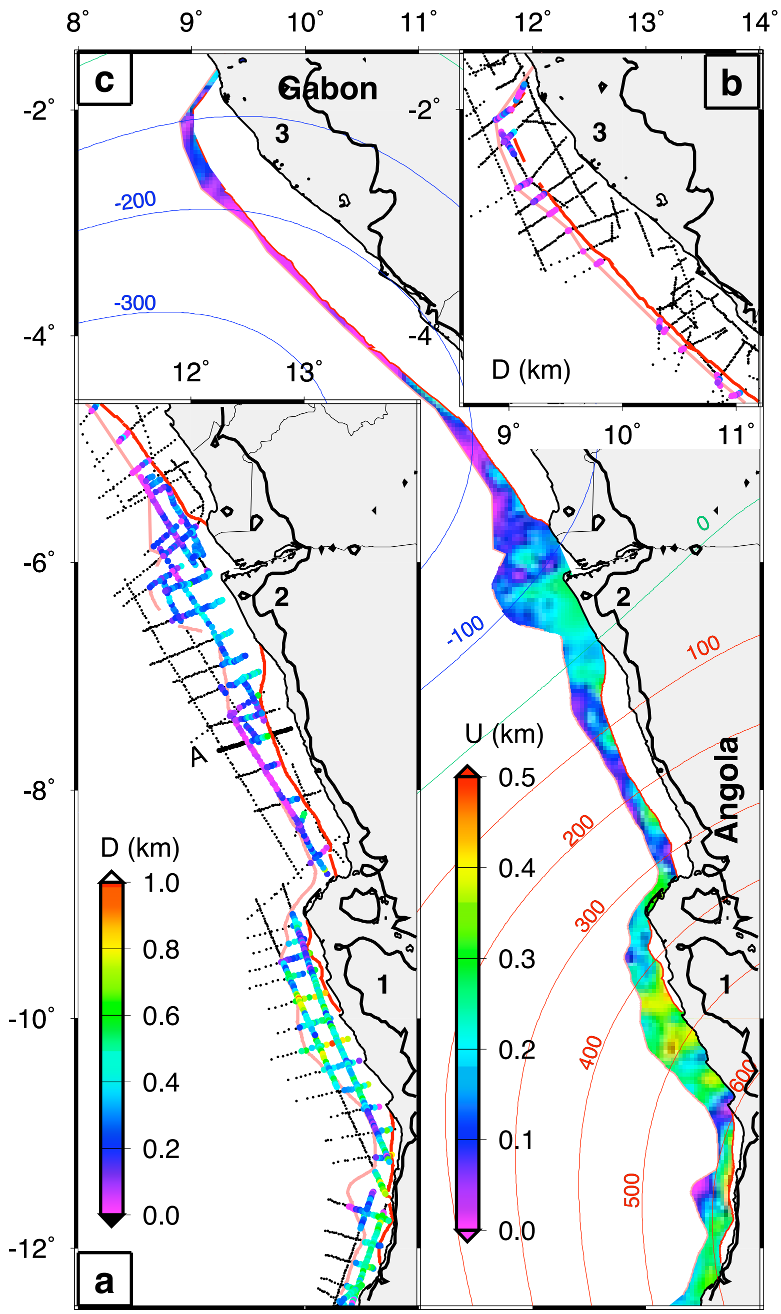

Figure 3: Calculated denudation and uplift maps for study area (see Figure 1 for location). (a) and (b) Map of denudation calculated by inverting root mean square (rms) velocity profiles. Solid black and colored circles = location of rms profiles used in this study where color indicates amplitude of denudation between seaward limit of seabed unconformity (solid pink line) and intersection of deeper Oligocene unconformity with seabed (solid red line); solid black line = 100 m elevation contour onshore; numbers 1, 2 and 3 = onshore portions of Kwanza, Congo and Ogooue deltas, respectively. (c) Map of uplift calculated from denudation by assuming Airy isostasy. Thin blue, green and red lines = predicted dynamic topography in meters calculated from long wavelength free-air gravity anomalies (Figure 1). Note that Ogooue delta at position 3 is at sea level and that Kwanza delta at position 1 is elevated by > 100 m and dissected. There is a significant seaward shift in location of 100 m contour at position 2 where Congo river debouches.

in order to constrain the spatial variation of post-Pliocene denudation. The smallest values of denudation (< 100 m) occur offshore Gabon down to 4° South. Approximately 500 m of denudation occurred across the Congo delta from 5–7° S, culminating in 1 km within the Kwanza basin at 8–12° S). Our results of post-Pliocene denudation generally accord with individual published estimates, which range from 150–500 m offshore the Lower Congo Basin to 1–2 km offshore the Kwanza Basin.

In order to compare our results to estimates of dynamic uplift, we have converted denudation into uplift (Figure 3c). Regional uplift steadily increases from north to south reaching a maximum of about 500 m at the Kwanza delta. This increase is in close agreement with the spatial distribution of dynamic topography predicted from the long-wavelength gravity field by assuming an admittance of Z=50 mgal km^{-1}. We conclude that this domal feature rapidly grew in the last 2 Ma. Onshore, the youthfulness of this dome is evident from strongly convex-upward drainage profiles and from the rapid increase in solid sediment flux at the Zambezi delta which occurred during Pliocene times when West Africa tilted eastward (*Walford et al.*, 2005). We suggest that this dome represents convective upwelling of hot upper mantle material. It inflated at a rate of $\sim 10^8$ km^3 Ma^{-1}.

There is no obvious relationship between the pattern of Oligocene uplift and present-day dynamic topography (*Al-Hajri*, 2006). We suggest that this earlier phase of uplift is related to initiation of the superplume beneath sub-equatorial Africa. The massive increase in solid sediment flux observed in major river deltas at 30–35 Ma provides corroborative support for this idea (*Walford*, 2003).

In conclusion, we have shown that post-Pliocene vertical motions along the West African continental shelf are caused by rapid growth of a large dome which was probably generated by convective circulation of the upper mantle. We suggest that other domal features have a similar origin. At much longer wavelengths, we concur that the topography of sub-equatorial Africa is maintained by a superplume which may have initiated in Oligocene times. If our ideas are correct, African epeirogeny supports the notion that two-layered mantle convection with distinct spatial and temporal scales is taking place beneath the plate.

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Providing tools to quantify the kinematics of uplift of Africa over the last 200 Myr.

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The African topography is characterized by elevated regions, such as the South-African plateau (> 1000 m), which do not relate to any orogenic setting. Several models have been proposed in the literature to account for these topographic anomalies, but can not be discriminated because of the lack of clear geological constraints on the history of uplift. To solve for this, our group has recently quantified fluxes of silico-clastic sediments preserved in the margins, and has re-assessed the evolution of the continental surface by re-interpreting paleo-geographic constraints and by gathering available low-temperature thermochronological data. All these data represent the sedimentary archives of past uplifts and topographies over the continent, and are therefore expected to be key to constraint the kinematics of uplift. In addition, the paleo-climatic evolution of the continent has been reappraised over these same time scales by gathering and re-interpreting observations reported in the literature.

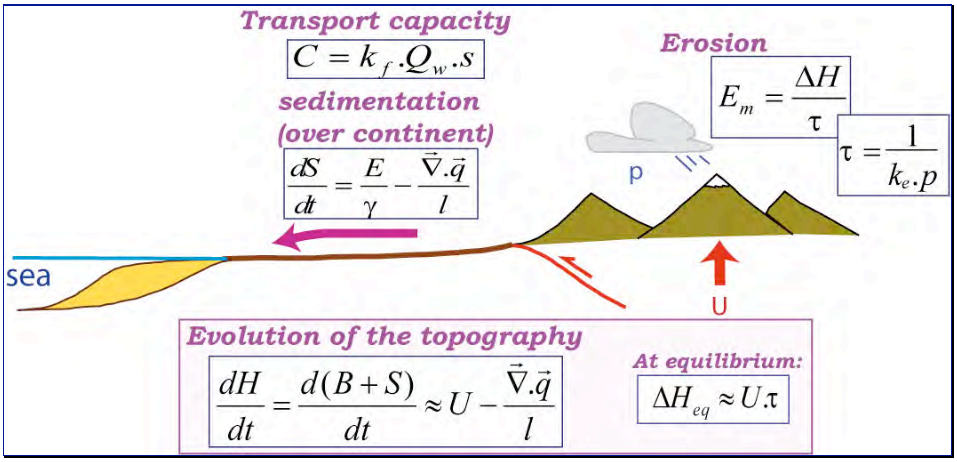

Figure 1: *Schematic view of erosion and transport laws as transfer functions between sedimentary data and topography or uplift. The laws proposed in this study are illustrated. In the erosion law, τ is the characteristic time scale, and depends on the bedrock erodability k_e and on the precipitation p. The transport capacity C depends on a transport coefficient k_f, on the regional discharge Q_w and slope s. When the sediment volume available in a region is greater than the transport capacity, sediments are preserved over the continent.*

To quantitatively interpret these sedimentary archives in terms of uplift and topography over the last 200 Myr, erosion and transport laws are needed (figure1). In particular, because of the huge spatial scale of our target (the African continent), and because of the crude resolution of our data, the laws to be used should integrate the diverse elementary geomorphic processes (rivers, hillslopes...) over large spatial and temporal scales (~100-200 km). Inspired by previous studies on landscape evolution based on numerical and physical modeling, we propose very simple laws for erosion and sediment transport (figure1). In particular, we suggest that erosion (= sediment production) is proportional to the mean elevation of a region over its base level, with a coefficient that corresponds to the characteristic response time of the landscape. This law for erosion has been quantitatively tested in light of physical experiments conducted in Géosciences Rennes, and in light of available data on present-day denudation rates and sediment yield measured in large ($\geq 10^4$ km²) river basins. In the case of the transport law, a simple proportionality between the transport capacity and the regional discharge and slope is considered (figure1), but should be more clearly investigated. Together, these laws describe how topography evolves over time as a response to tectonics and climate.

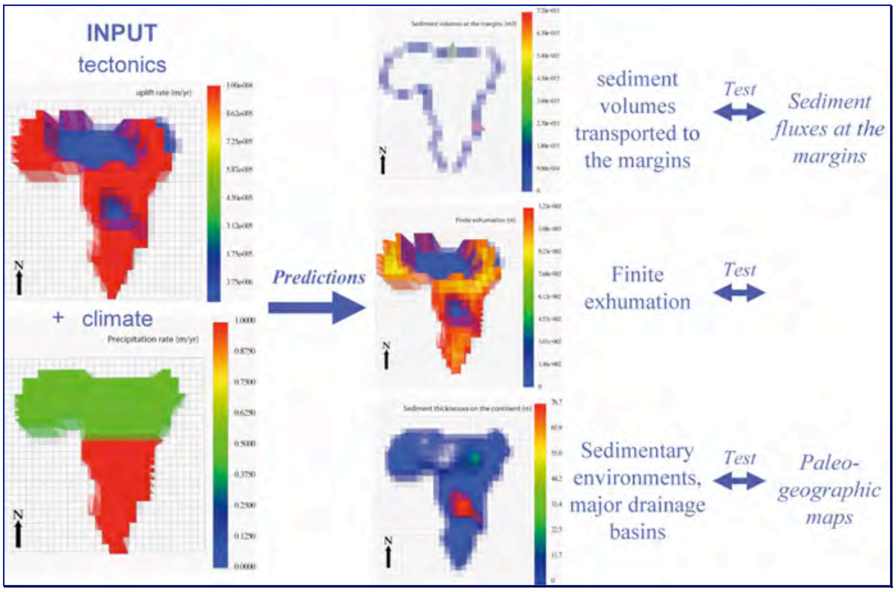

Figure 2: *Forward modeling using the code TOPOSED***.**

Finally, we have implemented these laws into a numerical code, *TOPOSED* (figure2). This code is able to predict how topography evolves as a function of the spatio-temporal distribution of uplift and precipitation over the continent. For a given tectonic and climatic scenario, the model is able to quantify the sediment fluxes transported towards the marginal basins, the stratigraphic state of the continental surface and the total denudation. The tectonic scenario implemented can then be simply validated by the capacity of the model to reproduce the various geological constraints (figure2).

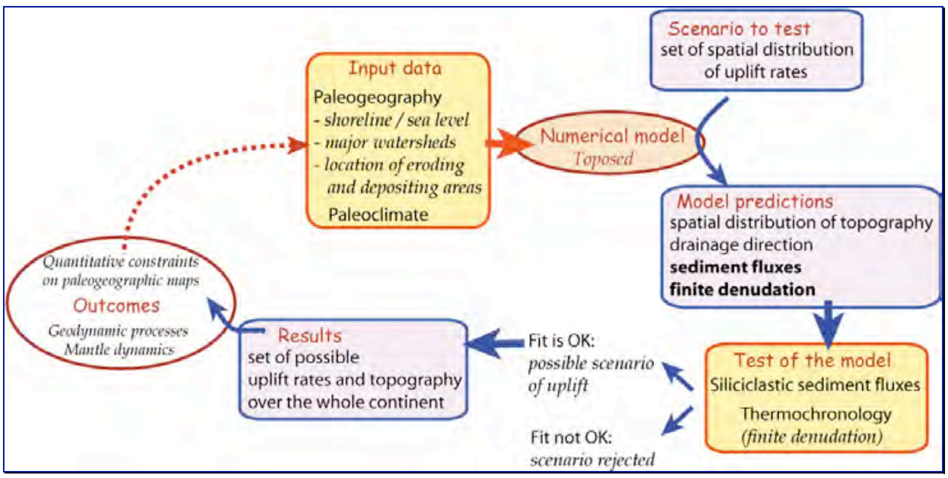

Figure 3: *Chartflow for the inversion of sedimentary data.*

In the future, *TOPOSED* is to be coupled to an inversion algorithm to extract all possible scenarios of uplift consistent with available data (figure 3). We have carried different tests to check the sensitivity of the model predictions to the spatial and temporal variations of uplift and precipitation during the time interval represented by the data, and to the uncertainties on the values of the erosion and transport coefficients. From these tests, it appears that the kinematics of uplift should be clearly constrained from existing data on the sedimentary fluxes at the margins. However, the evolution of the topography should be poorly constrained because it is highly sensitive to the details of the tectonic and climatic input. For this reason, a permanent feedback between model predictions and geological constraints (such as paleogeographies) will be necessary to check the plausibility of the model predictions.

Age and nature of lateritic weathering, erosion rates and long-term morphogenesis

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1. Introduction

Most of lateritic deposits and tropical soils result from long-term meteoric weathering of various rocks of the continental lithosphere and are still widespread on the Earth surface, especially throughout the tropical belt. Following the Gondwana break-up, physical and chemical processes led the development of tens meters thick weathering mantles including bauxites, ferricretes and/or mangancretes, which are actually preserved on relics of planation surfaces and/or pediplains on the shields (Millot, 1970; Bardossy and Aleva, 1990; Tardy and Roquin, 1998). The age determination of paleosurfaces and their lateritic weathering remains a critical issue to calculate the erosion rates and to constrain the Cenozoic evolution of continental palaeoclimates and long-term tropical morphogenesis.

2. Distribution and characterization of lateritic landsurfaces

In Africa, successive episodes of incision, weathering and erosion have permitted the formation and preservation of various types of lateritic crusts, which actually cap stepped relics of planation landsurfaces (King, 1967; Partridge and Maud, 1987). These obvious geomorphological relics abandoned by the past channel networks represent markers of the successive drops of local base levels (Chevillotte et al., 2006). According to the synthetic morphogenetic sequence described in west Africa by French authors (Michel, 1973; Grandin, 1976) and understood by others (Thomas, 1994), the highest surface with bauxite dominate differentiated landforms bearing different generations of ferricrete. On specific rocks, manganese ore deposits may develop within their associated weathering mantles (Figure 1). Downslope the bauxitic surface, the intermediary ferricrete-capped convex relief (the "relief intermediaire") dominates three ferruginous pediments defined as the high, the middle and the low glacis (Figure 1).

3. Age(s) of lateritic landsurfaces and erosion rate(s)

A relative chronology of the lateritic landsurfaces allowing estimation of erosion rate can be assessed by the measurement of elevation differences between these landsurfaces and the geochemical analysis of the associated lateritic materials. The highest is a landsurface the oldest is the associated laterite ; also the richness in Fe_2O_3 and-or Al_2O_3 and the poverty in SiO_2 and-or quartz of a laterite is indicative of its age (Tardy and Roquin, 1998). Assuming a minimum age of 1 Ma for a saprolite of 10 meters (Nahon, 2003), the age of bauxite being 60 Ma, Tardy and Roquin (1998) have proposed ages for ferricretes of the intermediary and glacis landsurfaces making the hypothesis of a linear variation of (Fe_2O_3 + Al_2O_3) content and-or a linear and exponential decreasing of quartz content with time. The estimated ages are 40, 29, 21 and 17 Ma for the ferricrete of the intermediary landsurface, the high, the middle, and the low glacis respectively (Table 1).

The elevation difference between each landsurfaces and glacis in different regions of the West African shield allow the estimation of erosion rates from the West African marginal upwarp (the Leo rise) towards its bounding sedimentary basins (Table 1). The results, even approximate, suggest erosion rates higher during the Eocene period and in the upslope area than during the Oligocene and Miocene and in the downslope area of continental scale drainage networks (e.g., Niger river).

4. Radiometric ages of mangancretes

The occurrence of K-Mn oxides (cryptomelane) in supergene manganese ore deposits has motivated the use of ^{40}K-^{40}Ar and ^{40}Ar-^{39}Ar methods for dating the mangancretes (Vasconcelos, 1992, 1994; Ruffet et al., 1996). These methods yield powerful dating means of past weathering and erosion periods provided that cryptomelane be a geochemically closed mineral.

Various generations of K-Mn oxides were dated by the Ar-Ar method in the manganese ore deposit of Tambao in North Burkina Faso (Hénocque et al., 1998; Colin et al., 2005), where the four West African geomorphological units discussed above characterize the landscape (Figure 1). Although an increasing diversity of ^{40}Ar-^{39}Ar ages is observed from the bottom to the top of the Mn-deposit (Figure 2) three main weathering periods can be defined (Figure 3). The first period from 59 Ma to ca 44 Ma is defined by Ar-Ar ages obtained in the upper part of the ore deposit. This characterizes a long weathering period lasting from middle

Paleocene to middle Eocene, during which bauxites formed all over the world (Bardossy and Aleva, 1990; Colin et al., 2005). The second period occurs in the range 27-23 Ma, and it is well characterized in the mid-part of the ore deposit. The third and last period, defined by Ar-Ar ages of cryptomelane located in the lower part of the deposit, is characterized by a succession of short weathering episodes between 18 and 3 Ma.

5. Lateritic weathering, palaeoclimates and long-term morphogenesis

The petrographical and geochemical patterns (including profile thickness) of the different lateritic landsurfaces could reflect differences in duration of weathering and erosion periods linked to contrasted climatic conditions between the Palaeogene and Neogene. The ^{40}Ar-^{39}Ar ages and the time intervals between these ages could document major episodes of lateritic weathering and mechanical erosion, respectively (Figure 3). The comparison of age distribution with the coastal and intracontinental sedimentary data, and the eustatic and $\delta^{18}O$ curves (Haq et al., 1987; Zachos et al., 2001) (Figure 3) also contributes to better understanding Cenozoic palaeoclimate changes records by West African landscapes.

From Palaeocene (ca. 59 Ma) to middle Lutetian (ca. 44 Ma), $\delta^{18}O$ is low (Zachos et al., 2001), the eustatic level is high (Haq et al., 1987) (Figures 3a and 3b), and the sediments of continental and marine African basins are mainly composed of carbonates, marls, and clays dominated by sepiolite, palygorskite and attapulgite (Millot, 1970) that indicate a chemical and biogeochemical sedimentation, which was characterized underneath the basal unconformity in the Iullemeden basin, 150 km North North-East and East of the Tambao deposit. This biogeochemical sedimentation is also linked to the development of thick lateritic weathering mantles including bauxites but also ferricretes and-or mangancretes on the neighbouring lands.

Bauxites were also described on the unconformity (Figure 4) between the siderolithic (Oligo-Miocene) including ooliths lenses and the attapulgite-rich deposits in the Iullemeden basin (Faure, 1966; Lang et al., 1990). A ferricrete specific of the intermediary surface was described above the sediments of the Continental Terminal (CT) of Mali and Niger (Gavaud, 1977). Relics of a similar ferricrete are also present at the upper surface of Tambao ore deposit where ^{40}Ar-^{39}Ar ages of 59-44 Ma were measured. These field observations and Ar-Ar data imply that the bauxitic and intermediary ferruginous paleolandsurfaces intersected near Tambao (Figure 4). A rate of 2.5 m. Ma^{-1} for the sinking of the oxidation front is estimated for the period 59-44 Ma.

No significant Ar-Ar age was obtained in the range 44 - 29 Ma (Figure 3c). Incision and erosion of previous lateritic landforms were the dominant surface processes; and the continental sedimentation (siderolithic CT) reworks lateritic materials eroded from the upper landsurfaces (bauxitic and intermediary) (Figure 4). The high glacis landsurface is characterized by the reworking of coarse materials originated from the upper lateritic surface profiles (bauxite and intermediary) that is characteristic of glacis forming surface processes under drier climatic conditions. The occurrence of dryer climatic conditions on continents coincided with the Oligocene global cooling (Zachos et al., 2001), and sea level drop at ca. 34 Ma and ca. 29 Ma (Figure 3b). On the basis of the relative elevations of dated cryptomelane (Figure 2) an average erosion rate of 1.5 m. Ma^{-1} is estimated between 44 and 29 Ma in the Tambao region.

The next major period of chemical weathering in Tambao occurred around 27-23 Ma (Figure 3c) and it is well defined at the top of the high glacis. This age interval could date the ferruginous weathering of this landsurface and possibly the reactivation of earlier lateritic profiles (e.g., intermediary). This could also be the age of the older ferricrete observed on the CT sediments (Figure 4).

From the early Miocene, the climate of the Earth was driven by a glacial/interglacial dynamic with a higher climatic gradient between the poles and the equator. The two lower ferruginous glacis could have been formed from this time, resulting from high frequency climatic oscillations between 23 and 3 Ma that have led short weathering-erosion episodes rather than long and intense weathering period (Figure 3c). The rates of the oxidation front sinking and mechanical erosion are on average equivalent (e.g., 2.5 m. Ma^{-1}) for this period.

6. Conclusion and perspectives

West African stepped lateritic landsurfaces bearing various lateritic materials gauges successive stages of the continental morphogenesis including Cenozoic weathering and erosion periods. The quantification of level differences between each landsurface coupled to the petrological analysis of the associated lateritic material (bauxite, ferricrete) is a first approach to estimate their relative ages and the erosion rates at different time spans.

Radiometric ages of mangancretes contribute to better constrain these ages and the rates of weathering and erosion if the embedding ore deposit is comprehensively integrated in a well-defined geomorphological sequence. Ar-Ar ages obtained in West Africa confirm that the bauxitic and ferruginous landsurfaces are old and that lateritic weathering is continuous at least for 55 Ma.

The large scale mapping of the main lateritic landsurfaces (bauxitic and ferruginous) and the establishment of their spatial relationships with the sedimentary limits are now required to better quantify continental scale denudation rates.

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Lateritic landsurface	Estimated age (Ma)	*Elevation difference (m)	*Erosion rate ($m.Ma^{-1}$)	#Elevation difference (m)	#Erosion rate ($m.Ma^{-1}$)
Bauxite	60				
		300	15	100	5
Intermediary	40				
		150	13-14	35	3-4
High glacis	29				
		100	12.5	20	2.5
Middle glacis	21				
		25	6-6.5		
Low glacis	17				

Table 1. Age and erosion rate estimation for the different lateritic landsurfaces of *(Guinea, Senegal and Mali), and #Burkina Faso around Aribinda from the geochemical composition of laterites and the measured elevation differences, respectively (After Tardy and Roquin, 1998).

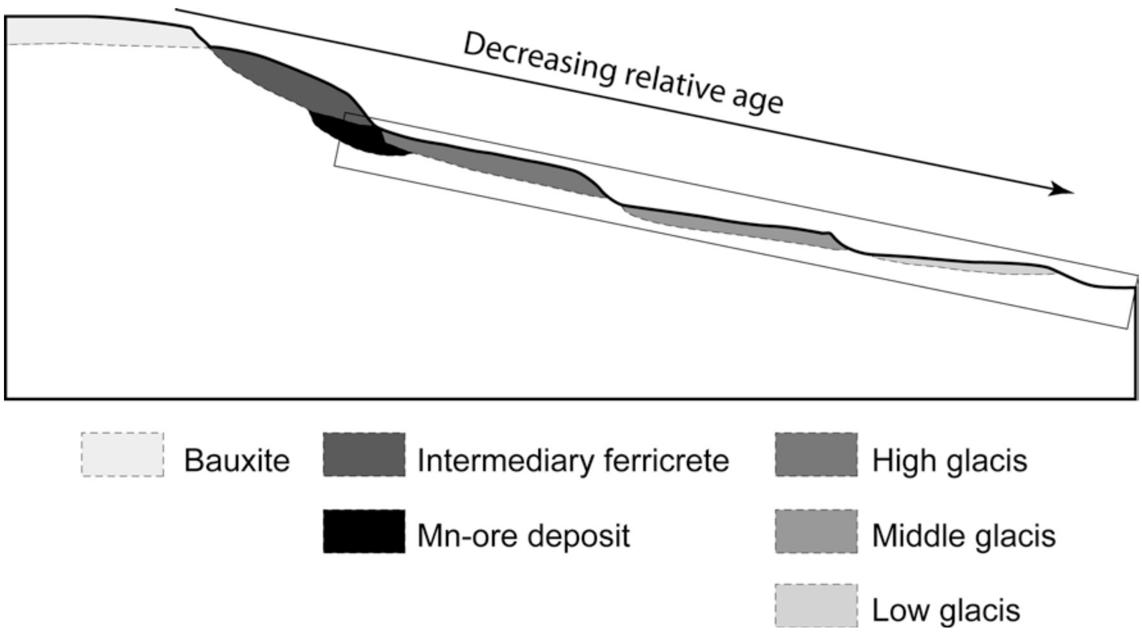

Figure 1. Synthetic geomorphological sequence of the stepped lateritic landsurfaces of West Africa. (The rectangle represents the geomorphological landsurfaces of Tambao area in North Burkina Faso).

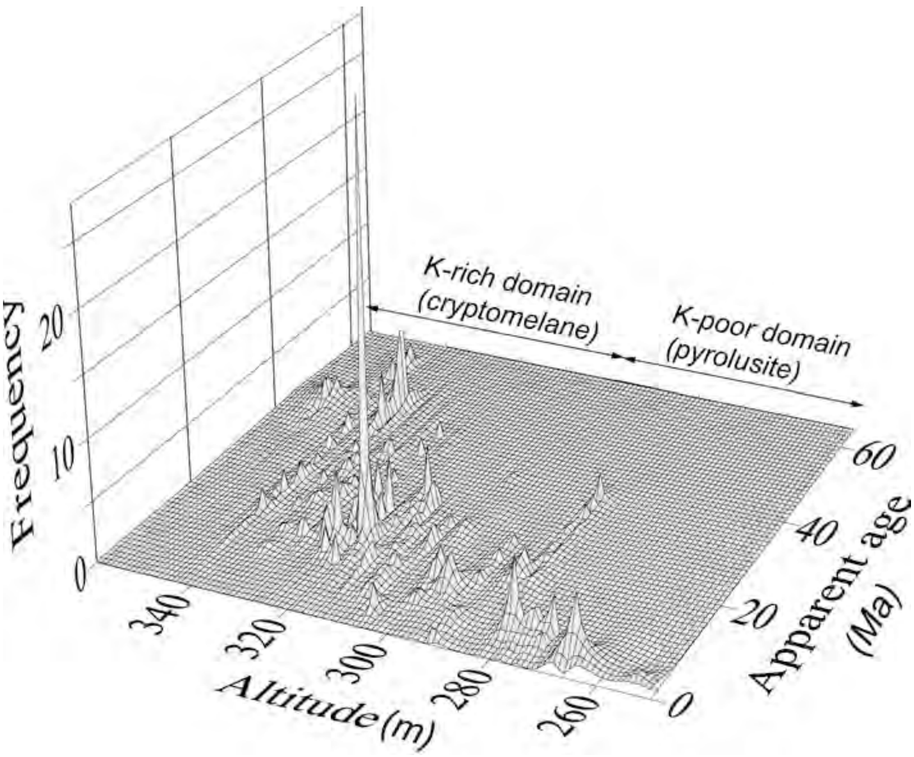

Figure 2. Frequency diagram of all Ar-Ar apparent ages obtained in the Tambao Mn-deposit.

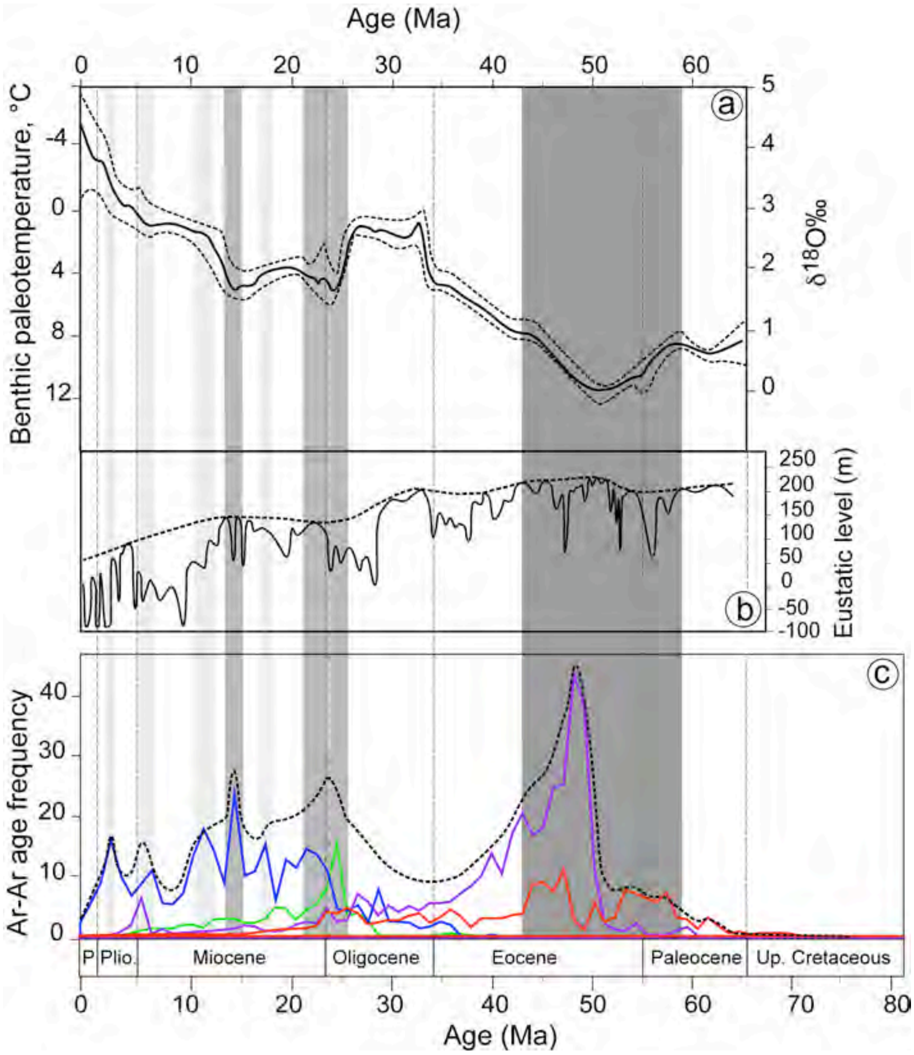

Figure 3. Comparison between (a) the global marine $\delta^{18}O$-paleotemperature curve from *Zachos et al*. [2001], (b) the eustatic level curve from *Haq et al*. [1987], and (c) the apparent $^{40}Ar/^{39}Ar$ age frequency curves. (the dashed curve in (a) represents maximum and minimum values, in (b) the first order eustatic curve, in (c) Ar-Ar age frequency curve for the deposit as a whole (violet = outcrop and surface samples; red = pisolitic formation; blue= high hill cores; green= low hill core; different grey scale bands represent groups of Ar-Ar age according to the intensity and duration of the corresponding weathering episode. Periods more propitious to erosion may occur between the Ar-Ar age groups).

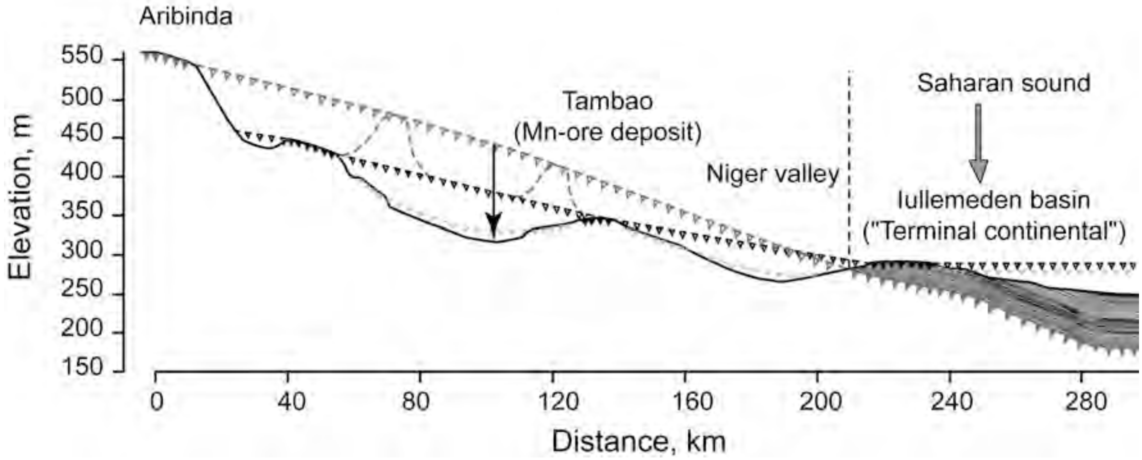

Figure 4. Geomorphological relationships between the lateritic paleolandsurfaces and the sedimentary limits of the Iullemeden basin of Niger in West Africa. Bauxite (grey), intermediary ferruginous (black), high glacis (light grey). Denuded bauxite relics are represented by the trapezoidal dashed figures and the vertical black arrow represents the total denudation of the regolith.

Rates and styles of continental denudation: Clues from river geochemistry

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Rivers are messengers from the surface of the Earth. They average the diversity of sources and processes that transform bedrocks into sediments. Denudation of continental surfaces occurs mechanically or chemically (transformation of the bedrock sediments) and the resulting products are transported by rivers either in a dissolved form (solutes) or as suspended sediments and bottom sediments. The question that we want to address is: what did we learn from the geochemical investigation of the erosion products transported by rivers?
In the last decades, geochemists have developed a number of tools and focused on a number of river systems, at different scales, to answer this question. We will review the main results of these investigations and see what are their inputs, particularly for the evolution of continent topography, which is one of the controlling parameters determining the composition of river sediments and river waters.

River data, when corrected from atmospheric inputs, lead to average erosion rates. These rates show a large range of variation at the surface of the Earth and are clearly higher for drainage basins draining mountainous areas. Topography has thus a strong impact on the erosion rates and particularly the physical part. Ratios of mechanical over chemical erosion are much lower in lowlands compared to mountains. In Africa, the Congo river has chemical and physical erosion rates that are about the same. The erosion of volcanic rocks is extremely active in all types of climate with mechanical over chemical ratio that are clearly in favor of mechanical erosion. The study of volcanic drainage areas, is particularly interesting because the bedrock is known

Because the only witnesses of past weathering processes are the sediments that accumulated in sedimentary basins, the relations between chemistry of sediments and weathering context is important. The quality of the suspended and bottom sediments is clearly a function of the rate of denudation. Fast systems (with high erosion rates) produce sediments that are much less evolved than sediments produced in quiescent systems. Africa is typically a continent that produces highly evolved sediments from a chemical point of view. In particular, the sediments produced by the river systems in Africa are remarkably uniform in terms of granulometry. The Amazon river or Himalayan rivers produce much more heterogeneous sedimentary material and a strong relation between chemical composition and size of the sediments exist in the two later basins.

Rates and quality of sediments produced by drainage basin are related though the steady state concept of erosion. Geochemical data can be used to test the hypothesis of a steady state, in which the amount of sediment produced by chemical weathering is balanced by the amount that is exported. Large African systems appear to be in steady state, although it may not have been the case in the past.

The steady state concept is strongly dependant upon the timescales of erosion. To a given perturbation, different river systems will respond with different time constants. Recent progresses have been done by the use of uranium isotopes for determining the typical relaxation times of river basins.

All combined together these informations put strong constraints on the dynamic evolution of continental surface. The development of new tracers (in particular isotopic) and the study of adapted and simplified drainage basin has started to provide crucial informations on the evolution of topography and more generally on continental surface dynamics.

3D numerical modelling of the dynamic of the relief of African passive margins: implications for sedimentary systems and surface transfers.

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The African continent is bordered by passive margins and bears intracontinental basins preserving the terrigeneous sediment resulting from its erosion, and as such, recording the dynamics of its relief variation. The histories of the terrigeneous supply and denudation have most of the time been analyzed quite independently, mostly because, on geological time scales, the interpretation of sediment supply in terms of relief variation in the drainage area is far from straightforward. In that perspective, the understanding of sediment flux transfer from the drainage area to the sedimentary basin, at geological time scales (x10 Ma), is of critical importance.

In that perspective, the relief dynamic of passive margins becomes a key issue. Indeed, if the vertical movements along most passive margin remain subtle in comparison with tectonically active areas, their amplitude is sufficient to affect the onshore sedimentary systems (e.g. fluvial systems) which is responsible for the transfer of terrigeneous material to the offshore margin basins. The subsidence history of the margin therefore controls the capacity of these basins to preserve (or not) this supply. The vertical movements of a passive margin are mainly controlled by the thermal evolution of the stretched lithosphere, surface processes (erosion/sedimentation) and flexural isostatic compensation. The complex pattern of vertical movements resulting from this intrinsic behaviour can also be altered by the superposition of vertical movement induced by flow in the mantle or tectonically driven deformation.

Our objective is to determine and quantify the expression of these different types of vertical movements in the stratigraphic architecture of passive margins basins in general, and around the African continent in particular. The novel aspect of our approach is to integrate the evolution of both domains in erosion and in sedimentation (*i.e.* from the drainage divide of the domain in erosion down to the most distal deposits over the oceanic crust), in a 3D framework involving state of the art numerical modeling tools of the thermo-mechanical evolution of the lithophere (Flex3Dstrati, developed by J. Braun) and using advanced concepts in sequence stratigraphy.

In a first part, we compiled and homogenised the geometry and seismicity of the peri-atlantic margins from published data in order to define the reference geometry of a passive margin for the numerical modelling and to determine the variability in their style and geometry that can be expected (Figure 1).

In a second part, we analysed in details the Namibian margin located on the northwestern rim of the south African plateau, in part by conducting fieldwork. The objective was to determine the contributions to the margin topography from a range of proposed mechanisms : initial rift shoulder uplift, lithosphere flexure, mantle related doming, and how they are preserved in the present day relief (Figure 2).

In a third step, we performed a parametric analysis of the passive margin topographic evolution. The numerical tool (Flex3D) allows us to simulate the evolution of a lithosphere following an episode of instantaneous rifting and thinning, as well as the stratigraphic architecture of the resulting sedimentary basins by combining thermal, flexural module and surface transport modules. The objective was to quantify the influence of the initial geometry of the stretched lithosphere (*e.g.* length of the stretched lithosphere, initial geothermal gradient, necking depth; Figure 3) on the topographic evolution of the margin and the stratigraphic architecture of the basins (volume of sediment preserved, depositional sequences, etc…).

In a fourth step, we compared the predictions of the numerical model to the observed stratigraphic architecture of African passive marginal basins, in order to determine the 3D geometry of the initial rifting, the influence of factors such as the thermal state of the African lithosphere at the time of rifting, its mechanical strength (vertical position of the so-called "strong fiber") and whether additional vertical deformation (e.g. mantle dynamics, tectonics, etc…) or additional sedimentary supply (climate change altering the transport capacity of the continental sedimentary systems) need be superimposed.

The results of this study bring new constraints on the transfer and supply of sediment from the continent to the ocean on geological time scales (x10 Ma). They will be discussed in the framework of the TOPOAFRICA project that predicts, for a given uplift scenario, the sedimentary supply to the major sedimentary systems of the African continent.

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FIGURES.

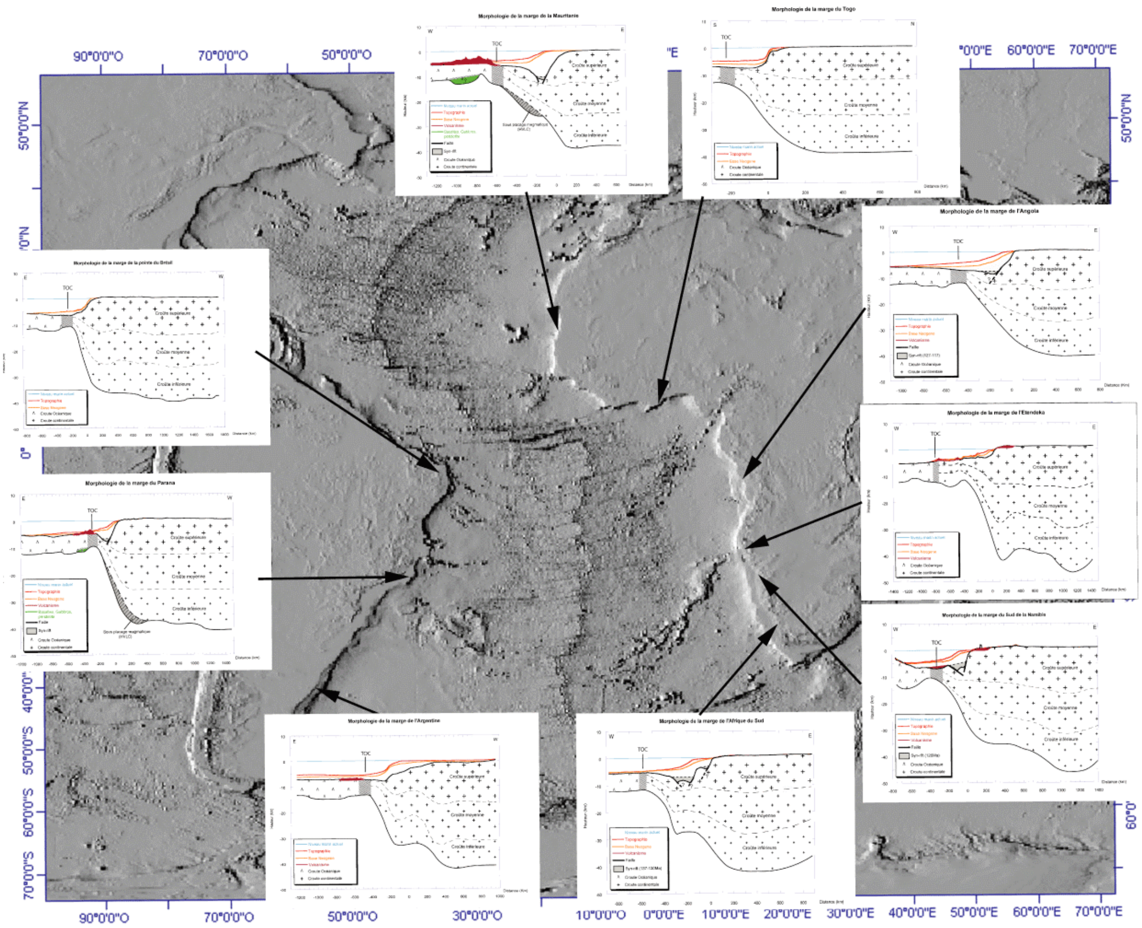

Figure 1: Synthesis of the geometries and seismicity of peri-atlantic margins used to determine the reference geometry for the modelling.

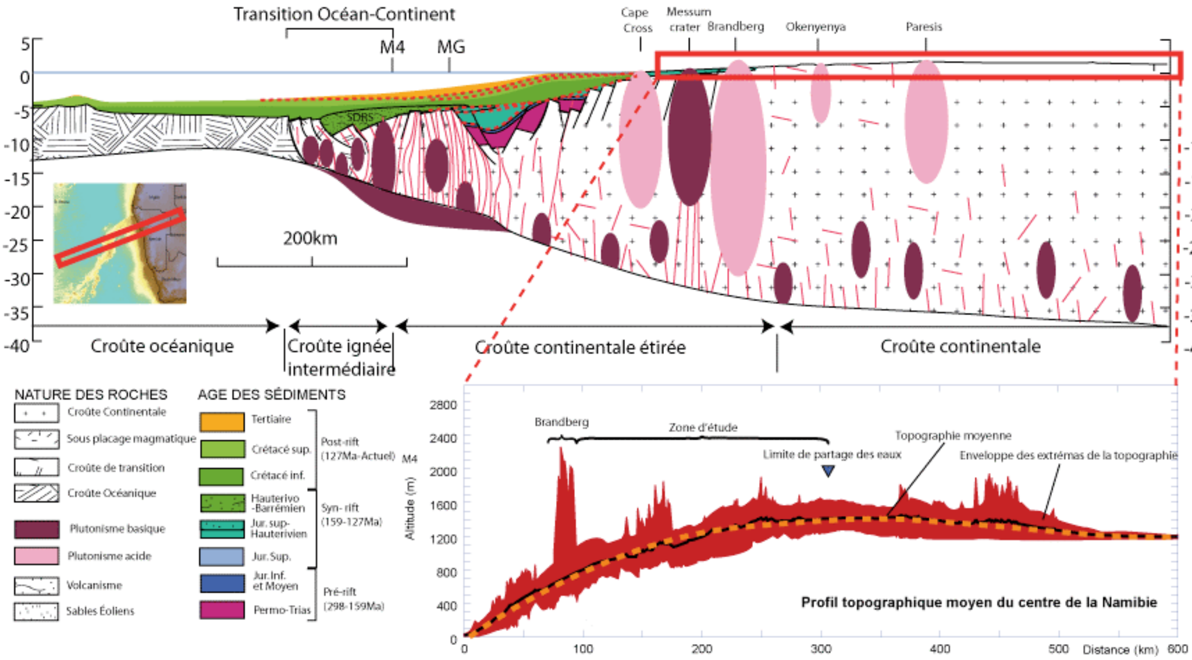

Figure 2: a) Synthetic cross-section of the Namibian margin. (Data : Bauer *et al.* 2000 ; Gladczenko *et al.,* 1998 ; Light *et al.,* 1993 ; Emery and Uchupi, 1984 ; Money *et al.,* 1998 ; etopo2, Geological maps). b) Margin morphology: Data SRTM and GPS .

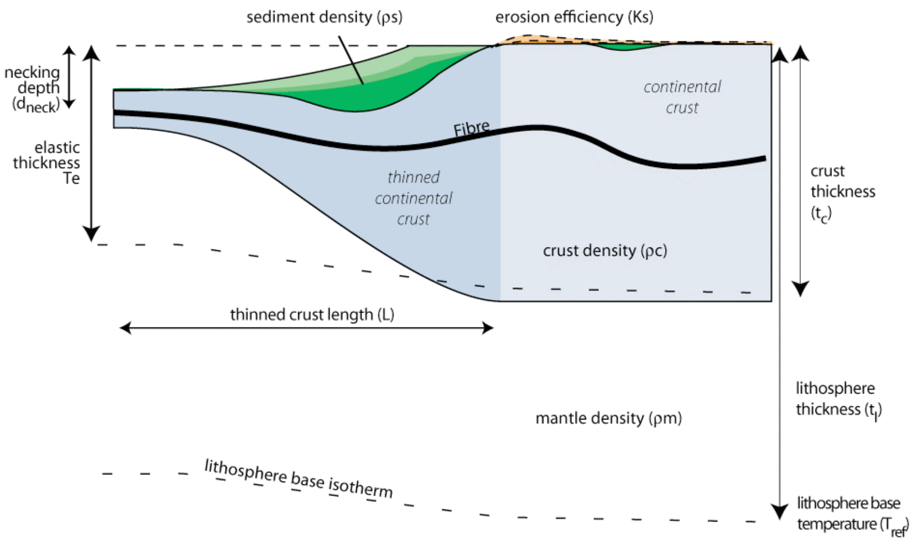

Figure 3: Parameters of the numerical analysis for their influence on the topographic evolution of a passive margin and its stratigraphic architecture.

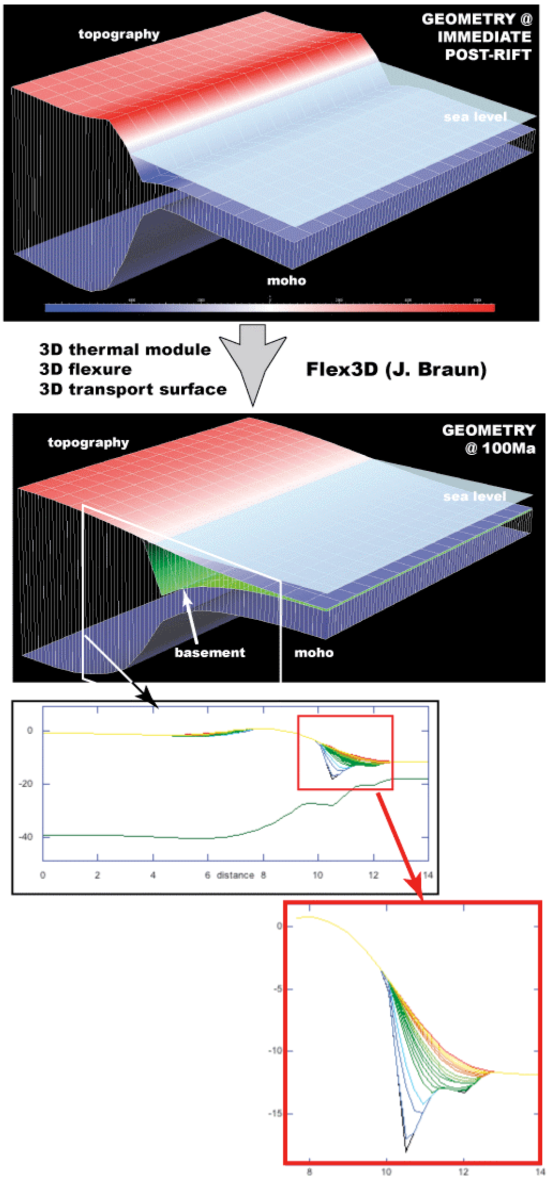

Figure 4: Schematic of the Flex3Dstrati modelling tool. The numerical tool allows to simulate the evolution of a lithosphere and the stratigraphic architecture of associated sedimentary basins combining thermal, flexural module and surface transport modules.

'Dynamic topography', global flow in the mantle and geoid anomalies: application to Africa

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South-Africa is uplifted and is situated above a 'megaplume' observed by tomography in the lower mantle. This uplift seems then an ideal case of 'dynamic topography' i.e. of topography induced by deep (deeper than 300km) mass anomalies and/or by large-scale mantle flow. But what is the amplitude of the expected 'dynamic topography' ? Is-it sufficient to explain the total African uplift or is there also a contribution from shallower mass anomalies (for example, lithospheric delamination). For more than 20 years (Hager and O'Connel 1981, Ricard et al. 1984), various models relating mantle mass anomalies, global mantle flow and geoid anomalies have been developped. Here we will outline the main differences among these models and discuss the implications concerning the predicted dynamic topography.

The simplest models involve a layered viscosity. The flow generated by mass anomalies, deduced from seismic tomography or plate reconstruction, induces topography at the surface and at the CMB. The total geoid anomaly is computed from the mantle mass anomalies themselves and from the induced mass anomalies corresponding to the surface and CMB topographies . In most cases the surface topography provide the largest contribution and gives its sign to the geoid anomaly (for example above a light plume, both the geoid and topography are positive). The viscosities of the various mantle layers are varied to achieve the best fit to the observed geoid. Among the numerous models proposed during the last 20yrs, all agree about a lower mantle significantly more viscous than the upper mantle. There is however a large scatter in the amplitude of the predicted dynamic topographies. In some models, the ratio between the predicted topography and geoid is larger than 10 and the 'dynamic' topography anomaly over Africa can exceed 1km (Lithgow-Bertelloni and Silver, 1998) while in some other models (Cadek and Fleitout, 1999, 2003), it can be as low as 200m. These models differ mainly by the hypotheses concerning the top 100km of the mantle (the plates) and the role of phase transitions.

Introducing the complex plate system in the models is not easy and up to now there has been no satisfactory solution:

Many models just do not have plates but instead a layer in the top 100km with a uniform viscosity intermediate between those of upper and lower mantle . These models are technically very simple and provide a rather good fit to the observed geoid. However the uniform viscosity soft surficial layer does not deform at all like plates...

One can impose plates with the geometry of present plates and try to compute the plate velocities in a consistant way from the stresses exerted by the flow at the base of the plates. However, up now, it was not possible to introduce in the computations some of the very small scale features in the subduction area (like the slab-channel) which influence strongly the plate velocities and 'plate boundary forces' were finally absent from these models; typically, there was no difference between subducting and overriding plates.

Imposing plate velocities is also easy, and, in our opinion does not induce spurious geoid predictions . However, this type of computation is criticized because it tells nothing about the forces driving plate motion.

Depending upon the strength of the lithosphere and the induced surface velocities, the topography associated with a given geoid anomaly will be different: typically, the predicted topography will be larger for models without plates.

Thirty years ago, there was a debate concerning 'two layer' versus 'whole mantle' convection. Presently, the tomographic images have convinced most researchers that slabs can penetrate in the lower mantle. However, phase transitions may act as a partial barrier to the flow: They may be deflected and thus be associated with mass anomalies which hamper the flow without totally stopping it. For example in the case of a rising flow associated with a light plume in the lower mantle, phase boundaries could be deflected upward, creating positive anomalies in the transition zone. Various mechanisms can induce such deflections of the phase boundaries: a negative Clapeyron-slope, thermal effects (Christensen U. 1998), volumetric effects, chemical diffusion...In the dynamic mantle models, these various effects can be parameterized using a 'layering coefficient' which is equal to zero if the phase boundaries are not deflected and equal to 1 if they are considerably deflected so that they impose a layered convection (no vertical velocity at 670km depth). It is rather obvious that 'partial layering' decreases strongly the predicted 'dynamic topography' (the phase transition is deflected instead of the surface).

Finally lateral viscosity variations have been introduced in the models. In models with surface plates, these lateral viscosity variations have a large impact: they allow a larger coupling between the deep mantle and the plates . A larger portion of the geoid is due to the plate velocities . The predicted dynamic topography is much larger over western Pacific than over Africa.

For models with imposed plate velocities, partial layering and lateral viscosity variations (Cadek and Fleitout, 2003), an excellent fit to the geoid can be obtained but the dynamic topography over Africa is very reduced (some 200m, see figure 1).

What data is there on the amplitude of the dynamic topography out of Africa?
This is not straightforward and it has been debated for many years. Around subduction zones, one may expect very large topographic depressions (Gurnis 1993). However, these are not conspicuous in the geological record: marginal basins have a rather normal bathymetry except for the Philippine plate which is too deep and the Fidji basin which is too shallow. The subsidence of the west-Pacific basins does not show clear evidence of dynamic effects (Weeler and White 2002). India, in its long northward travel, should have subsided as it overrided the cold lower mantle below the North Indian Ocean (Lithgow Bertelloni and Gurnis 1997). This does not seem to be the case as, in several Indian basins, cretaceous, eocene and oligocene sediments deposited in shallow seas are now presently on land at low altitudes.

The altitude of the world ridges seems influenced by their temperature rather than by dynamic effects (Klein and Langmuir, 1987, Lecroart 1997).

Finally, let us note that models which predict a large dynamic topography also predict large 'tectonic stresses '(10^{13} Nm). Such large tectonic stresses are unlikely because they would generate huge mountain chains (more than 15km high).

In conclusion, the predicted amplitude of the dynamic topography linked to deep anomalies and global mantle flow strongly depends upon the ingredients of the mantle flow model. It may not exceed a few hundred meters. In South-Africa, other processes, perhaps linked to the deep mantle plume but involving shallower mass variations (lithospheric delamination, ponding of hot material) are then necessary to explain a large part of the excess topography.

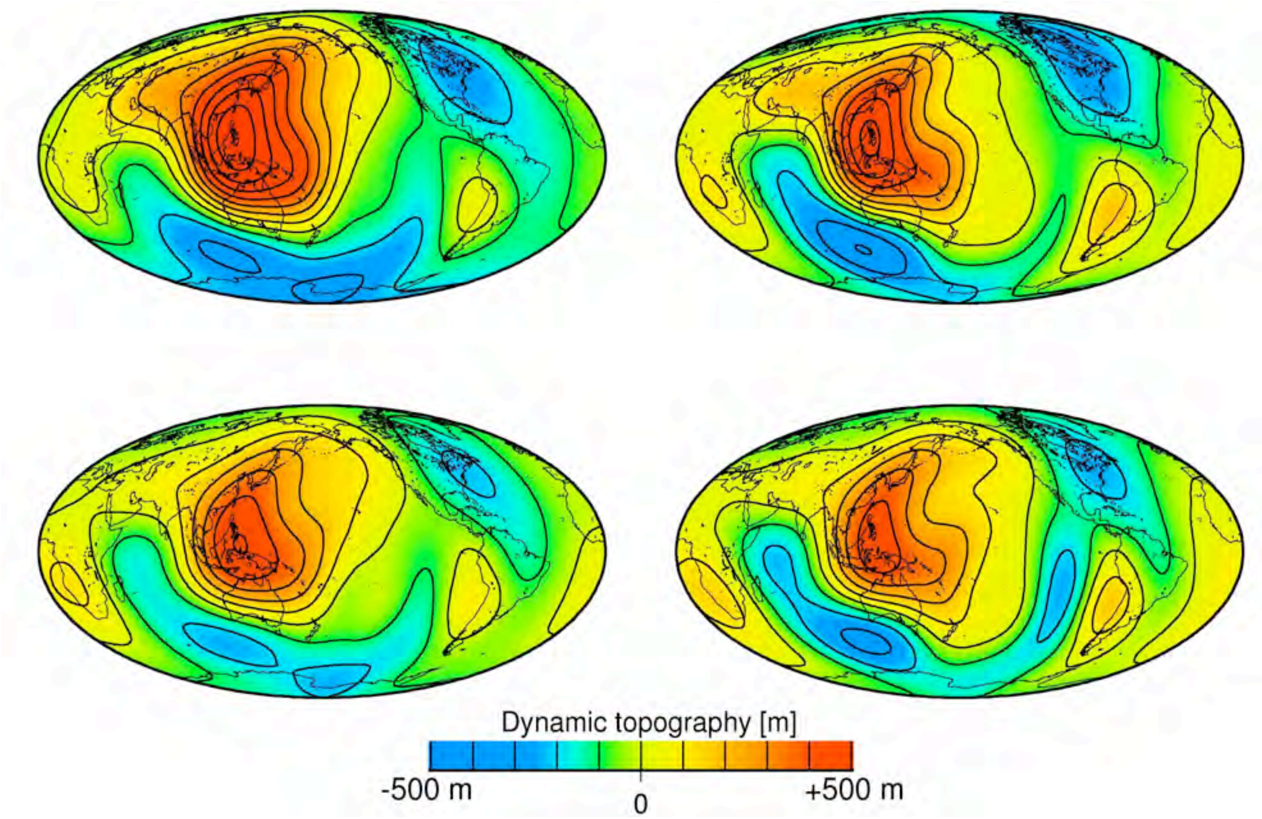

Figure 1: Predicted dynamic topography for various models fitting well the observed geoid (Cadek and Fleitout 2003). These models include partial layering and lateral viscosity variations.

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Geodynamics and vertical movements in the Maghreb during the Cenozoic

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Considering the topography of Africa (Fig.1), the relief of the Maghreb (which reaches 4165m at Jbel Toubkal) is the only one related, at least partly, to convergence between Africa and Eurasia. This convergence, active since Late Cretaceous, is responsible for

(1) wide lithospheric buckling
(2) inversion of Mesozoic basins (Atlas basins) inherited from a Triassic-Liasic rifting (Laville et al., 2004, and references therein).

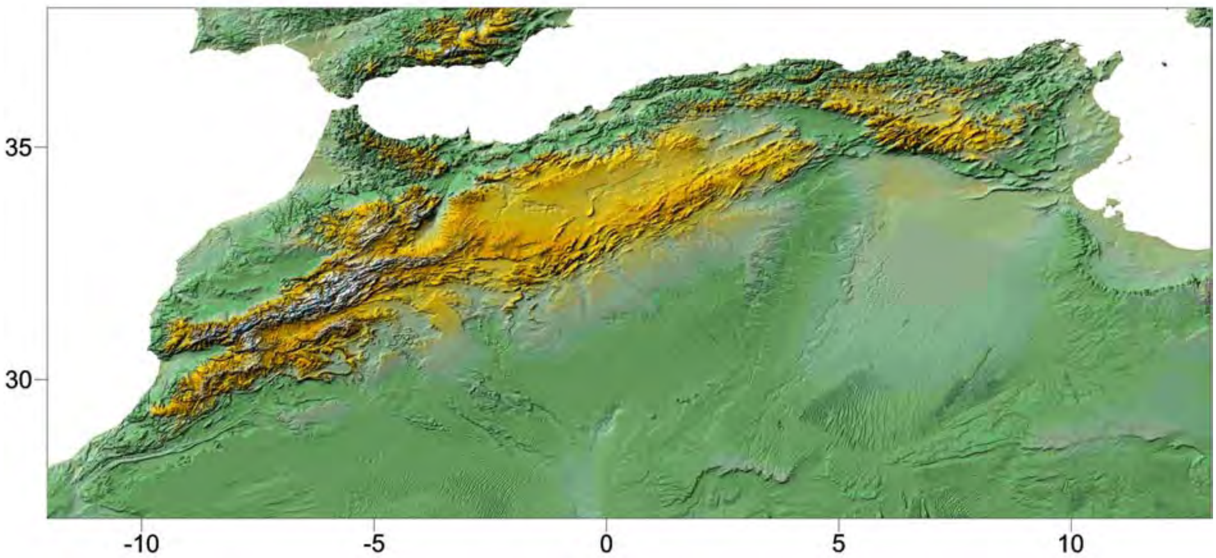

Figure 1: Topography of the Maghreb from SRTM. Note that the highest picks are located in Morocco where the foreland domain is poorly developed. On the contrary the widest and deepest foreland basin is Located in Tunisia and is associated to the lowest part of the orogen.

Buckling is evidenced since the Cenomanian from the paleogeographical maps of Vila (1980) showing wide E-W ridges with intervening basins (with wavelength larger than 200 km)
Inversion occurred more or less continuously since the Late Cretaceous. However relief building is restricted to short periods at the end of Eocene and during the Plio-Quaternary (Frizon de Lamotte et al., 2000). Before late Eocene and during the Oligo-Miocene, we observe, on the contrary a more or less important subsidence (fig. 2). In particular the Oligo-Miocene is characterized by accumulation of thick clastic sediments contrasting with the carbonate facies, which prevailed up to the Eocene.
We will discuss how these processes are linked to the West Mediterranean geodynamics.

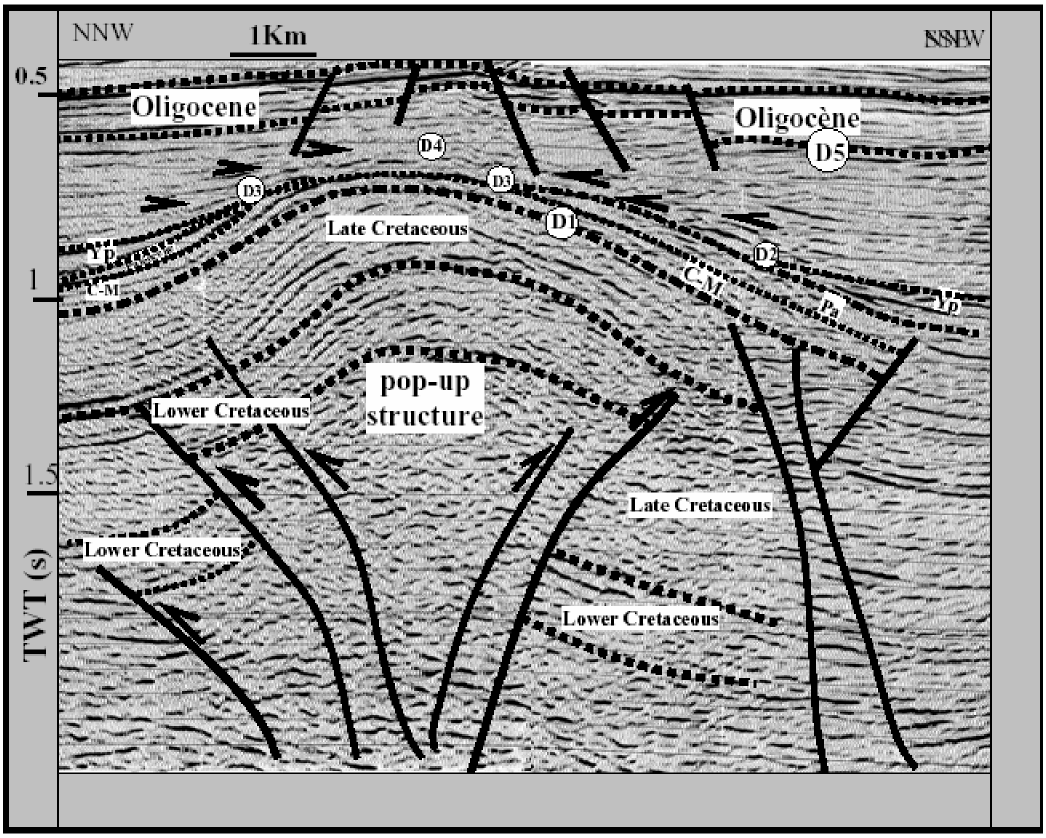

Figure 2 : Seismic Line in the Tunisian Atlas showing a pop up structure. The progressive unconformities during Paleocene and Eocene and the unconformity between Oligocene and older layers characterize a phase of relief building. On the contrary the overlap of Oligocene strata above the fold is typical of a subsiding period. In Tunisia this subsiding phase is accompanied by normal faulting (from Khomsi et al, 2006).

The problem is more complex in Morocco, where a thermal component is superimposed to tectonic structures and is linked to an oblique NE-SW strip of thinned lithosphere (Frizon de Lamotte et al., 2004; Teixell et al., 2005; Missenard et al., 2006), which cuts the South Atlas Front in the Siroua region, crosses the central High Atlas, follows the Middle Atlas and finally cuts the Eastern Rif front and finally reaches the Western Mediterranean (Fig. 3). In this zone the lithosphere/asthenosphere boundary lies at depth of ~60 km. It is underlined by a diffuse seismicity and by an intraplate-type alkaline volcanism (Miocene to Quaternary). Using geophysical modelling we can show that this thin lithosphere is responsible for 750 to 1000 m of elevation in Central High Atlas, in Middle Atlas and in Anti-Atlas.
To better constrain the orogenic growth of the Atlas system by identifying and quantifying episodes of vertical movements, we produced Apatite Fission-Track thermochronological ages from the Marrakech High Atlas and adjacent Anti-Atlas regions in Central Morocco, which were previously void of such data.

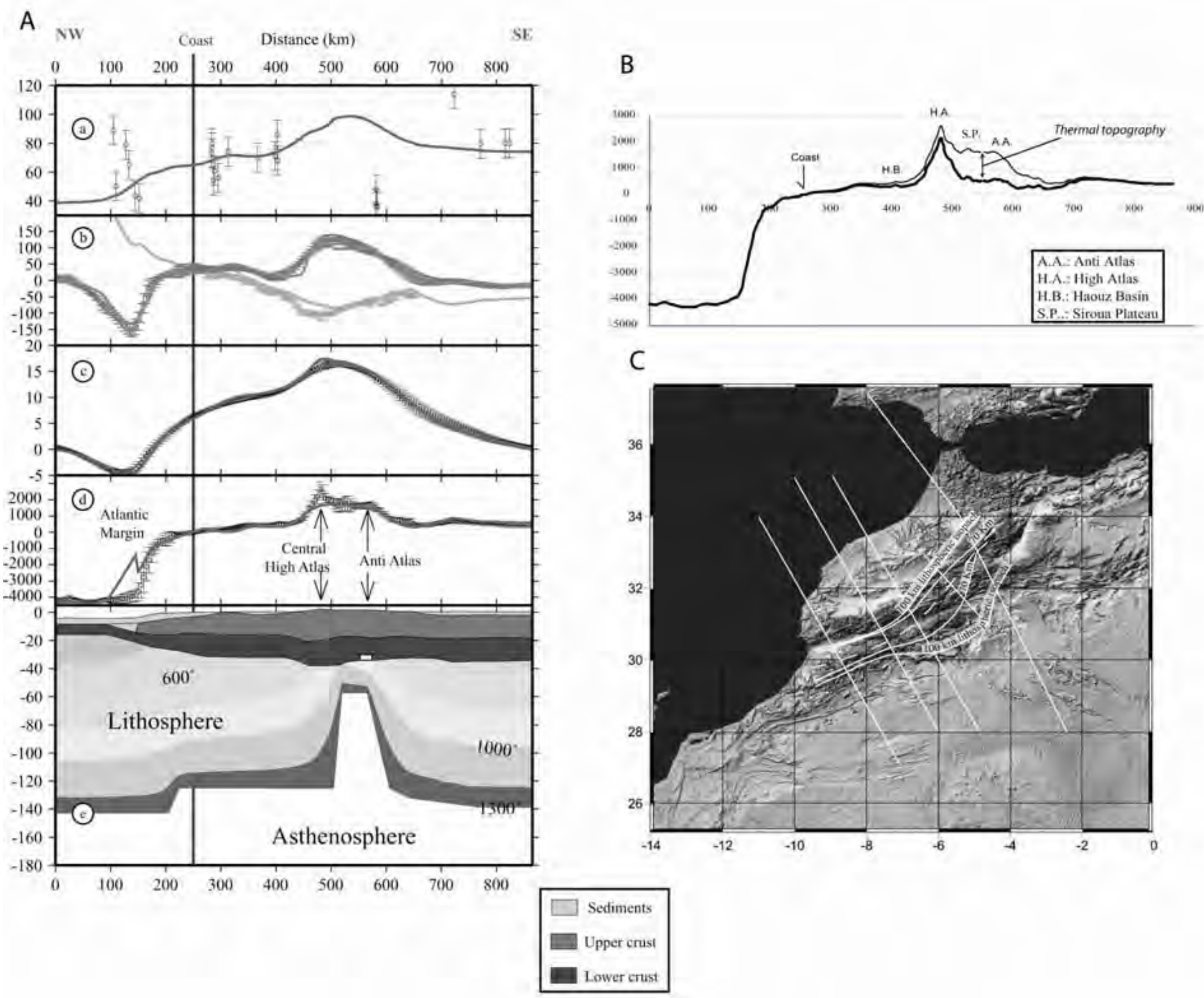

Figure 3 : A- Example of lithospheric cross-section model through High and Anti-Atlas. (a) represents heat flow, (b) free air and Bouguer gravity anomalies, (c) geoid, (d) topography, (e) resulting model with isotherms in the mantle every 200°C. Dots correspond to data extracted from world wide datasets with uncertainty bars and solid lines to calculated values; continuous lines in each box correspond to the calculated value for the model drawn in (e). (Modified from Missenard 2006) B- Comparison between actual topography (light gray) and topography without lithospheric thinning (bold line) calculated with the crustal model of figure 3A (modified from Missenard et al., 2006). C- GTOPO30 topography and isopach map of the lithosphere in Morocco as deduced from correlation between 5 lithospheric profiles (profiles from Frizon de Lamotte et al, 2004; Zeyen et al. 2005; and Missenard et al. 2006,

Samples from the inner Marrakech High Atlas are comprised between 9.2 ± 0.5 and 26.9 ± 2.6 Ma and get younger towards the bottom of the valleys (Table 1; Fig. 3), those ages are consistent with ages produced by Baliestrieri (2006). The altitude distribution of the samples in the Marrakech High Atlas allows us to calculate a rough denudation rate of 0.07 km/My for the Upper Oligocene to Upper Miocene period (25 to 10 Ma, Fig. 3). From a chronological point of view this period is situated between the two main phases of crustal shortening in the Atlas system in general (Frizon de Lamotte et al., 2000) and in the Marrakech High Atlas in particular (Missenard et al., 2007). So it is likely related to the thermal uplift, which took place between these two events (Missenard et al., 2006). Moreover, this Upper Oligocene-Upper Miocene period is also characterized by intense magmatic activity in the Atlas system,

with a highest alkaline volcanic production during the Middle Miocene (see review in El Azzouzi et al., 1999).
It is worth noting that the calculated denudation rate of 0.07 km/My cannot account for the total denudation until present. So, a major denudation event must have occurred after the Upper Miocene. According to the appearance of coarse conglomerates at that time in the foreland basins (Görler et al., 1988; El Harfi et al., 2001), this later event must be related to the second, Plio-Quaternary, phase of crustal shortening in the Atlas system (Frizon de Lamotte et al., 2000).

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SEA-LEVEL CHANGE DURING THE LAST 250 MY : NEW PERSPECTIVES IN QUANTIFICATION AND CAUSES

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Absolute sea level variations, is a reference level of primary importance in the Earth Sciences. Variations in sea level control part of the stratigraphic record for all of the world's sedimentary basins, the area of continental surfaces exposed to erosional processes, and the base level of the fluvial systems. Those variations have been used as a reference curve to estimate $p\mathrm{CO}_2$ variations, and the consequent climatic changes, through geological time.

The first objective of our project is to **quantify the sea level variations** for long (250 My) term time durations. The second aim is to constrain how the **lithospheric and mantle mechanisms** control these long and medium term sea level variations. We will focus on the Cretaceous (145-65 My), which displayed the highest sea level during the last 250 My.

Several long term sealevel curves (x100 km) for the past 250 My were published during the 70s and 80s (Pitman, 1978; Matthews, 1984; Haq et al., 1987). The most popular one is the one proposed by Haq et al. (1987). Most agree that sea level rise occurred from the Permian (270 My) to the Upper cretaceous (Cenomanian, 95-90 My, for Haq et al., 1987), and was followed by a sea level fall that continues today. Controversy persists, however (1) on the amplitude of this sea level variations (highest amplitude 350-250 m, McDonough & Cross, 1991, smallest 70-80 m, Miller et al., 2005), (2) on the kinematics of the sea level fall or rise and (3) about the required mechanism, which must be related to the plate movements, associated with the Wilson Cycle (Worsley et al., 1984 ; Veevers, 1990). This project is currently part of an international debate, between multiple groups working on those questions (sea Miller et al., 2005 for discussions).

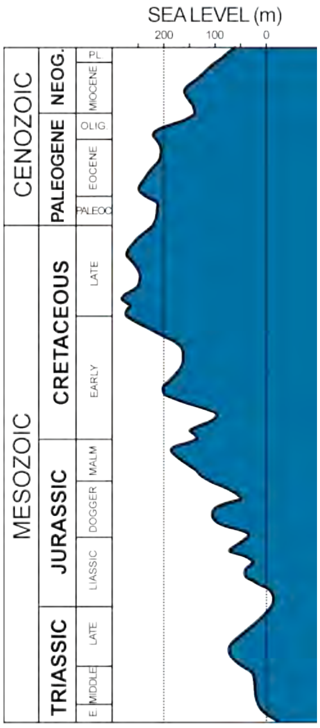

Fig. 1 : Eustatic chart (Haq et al., 1987)

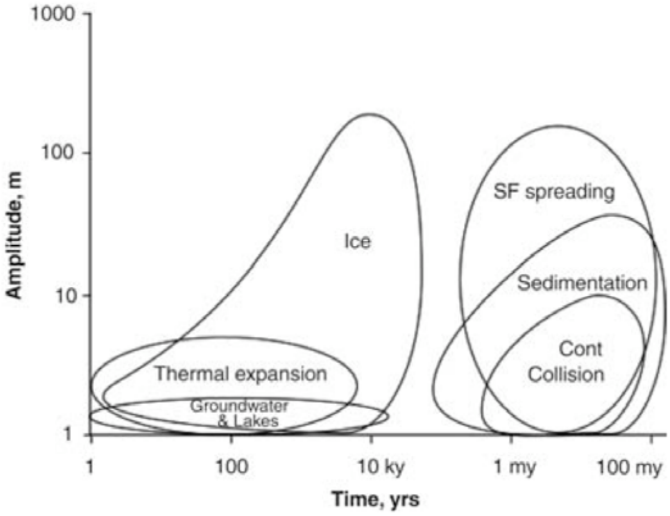

Figure 2 : Processus and eustatic amplitudes induced (Miller et al, 2005

Two main methods have been applied to quantify eustasy:

(1) the identification of a common signal among local measurements of relative sea-level change in different basins all around the world,

(2) the measurement of marine flooding over continents at a global-scale relative to the present-day topography (Harrison *et al.*, 1981; Ronov, 1994; Algeo & Seslavinsky, 1995).

Haq's curve, developed with support from the petroleum company EXXON, is based on the first method. Unfortunately, the source data were not published, and the correction for the long term thermal subsidence is a possible source of error. The estimate of the marine flooding (or coastal onlap) is based on world-scale paleogeographic maps.

The first part of our study will be based on the measurement of the marine flooding **on** continents through time. This method requires **new style world-scale paleogeographic maps**, quantified in term of **paleotopography**, to measure both the coastal onlap and the **hypsometry** of the Earth at each time-interval. The main challenge is the **quantification of the topography** of the Earth for Mesozoic times.

It is often suggested that eustatic fluctuations are primarily controlled by the mean seafloor age (Hays and Pitman, 1973) and the oceanic lithosphere accretionary rates (e.g. Kominz, 1984; Larson, 1991; Berner, 1994). Compare to these previous studies, we suggest that **variations in sea level** should instead be regarded as the product of (i) **isostatic processes in a steady convective regime**, (ii) **isostatic processes in a transient convective regime**, and (iii) **dynamic processes**, that exert a vertical traction beneath the surface of the Earth. Those are the topics of the second part.

Principles and methodology

Our method is based on a global-scale measurement of the marine flooding of continents on global paleogeographic maps. Sea level is inferred, for a given time interval, from the intersection of this world-scale flooding with the distribution of the world elevation, or hypsometry. The continental flooding is the percentage of the continental domain flooded by the sea. This percentage is defined from a specific geographic reference level that can be the shelf break or the present-day shoreline. The hypsometric curve is the cumulative curve of areas of land between pairs of contour lines as a percentage of the total land area.

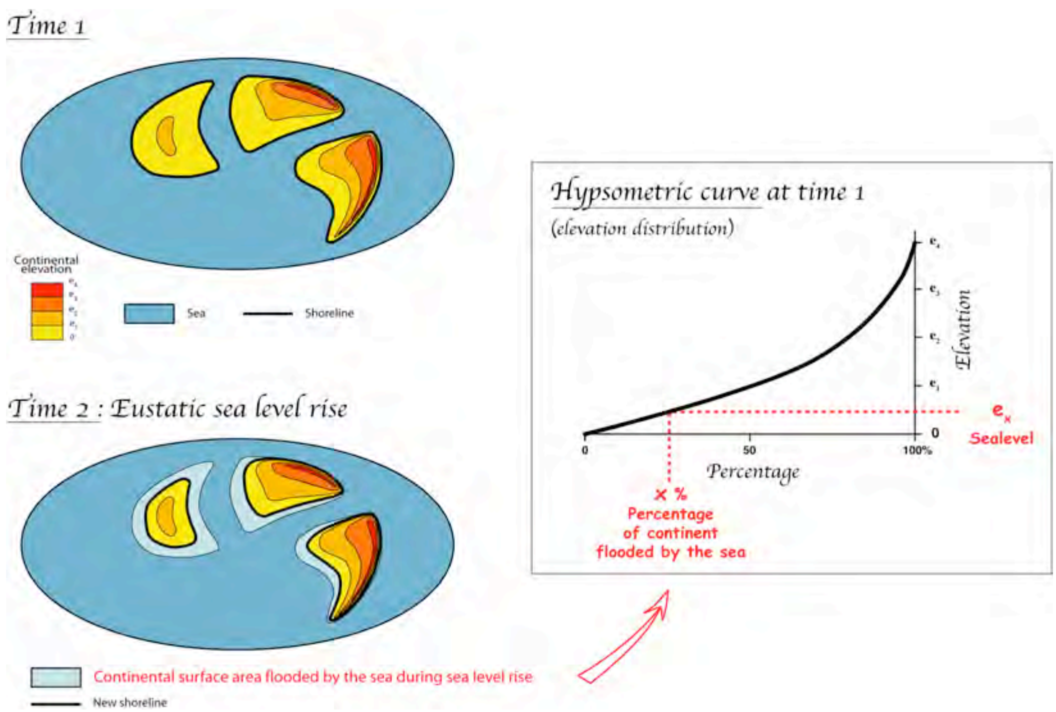

Figure3 : The sea-level is inferred, for a given time interval, from the intersection of this world-scale flooding with the distribution of the world elevation, or hypsometry.

We used a new paleogeographical dataset for the Meso-Cenozoic: one at a world-scale (project WGM/UNESCO "Changing Earth Face", Vrielynck & Bouysse, 2001), and one at a Tethys-scale (PERI-

TETHYS project, Dercourt *et al.*, 2000). We have compiled two tests of hypsometry: one for the present-day and another possible proxy for the Cretaceous topography : the Amazon catchment.

These results are based on the present-day continental hypsometry. The main rising question is: does the present-day altitude distribution apply for the past? Present-day continents are mainly subjected to erosion, and few subsiding domains (*i.e*. depositional system) occur. The present-day continental topography is different from the past one, mainly Upper Jurassic – Lower Cretaceous time, where large intracontinental basins (intracratonic basins, large passive margins, rifts…) with low relief, occurred. The present-day altitude distribution, which could be the best analogue of the Upper Jurassic-Lower Cretaceous time, is the Amazon watershed.

Using the Amazon hypsometry and the world-scale paleogeographic map (the only way to measure eustasy), the highest sea level occurs during Upper Cretaceous time (Cenomanian – Maastrichtian) and the amplitude would be +100 m above present-day sea level. Using Tethys-scale paleogeographic maps (eustasy + Tectonic deformations at Tehys-scale), the highest relative sea level occurs during Cenomanian time and the amplitude would be +250 m above present-day sea level.

Our preliminary results suggest that the most realistic value for the highest sea level of the Upper Cretaceous should be more around 100 m, smaller than 250 m as suggested by Haq et al. (1987). This finding is supported by new studies based on the **estimate of the accommodation** space at the scale of a passive margin (Miller et al., 2005) or by the world scale budget of the ocean volume (Cogné & Humler, 2006).

The main challenge of this project is to quantify the hypsometry of the Earth for past geological times and mainly the lowlands connected to the sea, possibly flooded by a trangression (the highest marine flooding is less than 18% of all the continents). Thus, the main effort will be focused on the paleogeographic maps for both quantifying the marine flooding and the paleohypsometry.

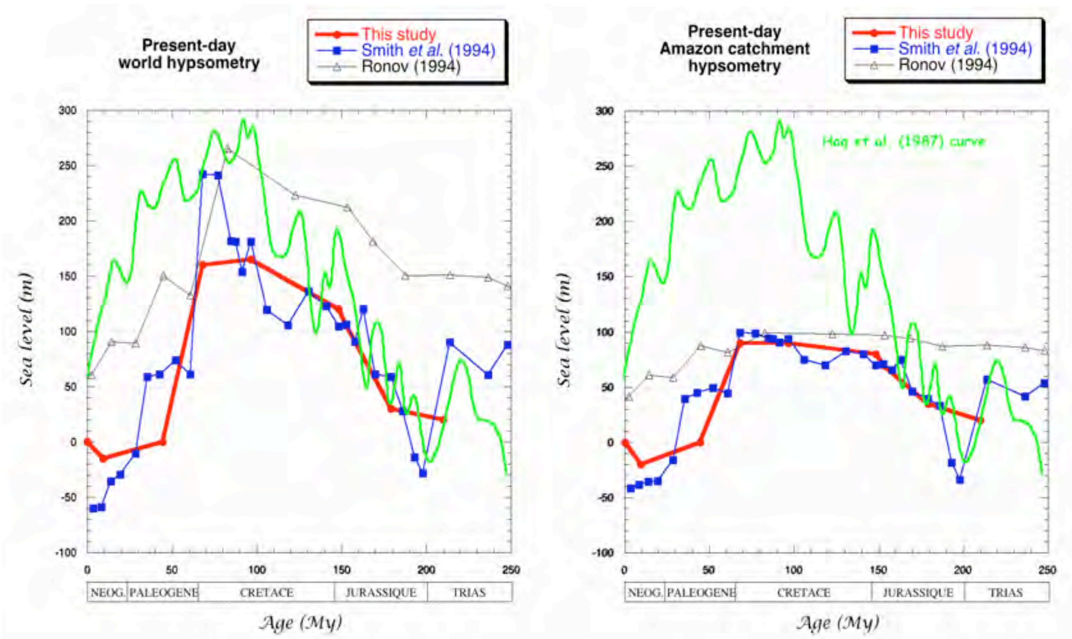

Figure4 : Preliminary results (Guillocheau et al., in prep).

The topography of the Earth during Mesozoic time: the way to build paleohypsometric curves

At the first order, most of the geologists agrees that the Earth topography is due to the vertical movements induced by the supercontinents breaking and merging cycles (Worsley et al., 1994; Algeo & Wilkinson, 1991). The paroxysm of continents clustering corresponds to the highest relief on the land, and reversely, for the paroxysm of continents dispersion. This scenario has never been confirmed using true geological data, such as world-scale paleotographic reconstructions maps.

Few studies have been carried out to quantify the relief of the past. The only published data are the ones of geologists working on world-scale paleogeographic maps (Smith et al., 1994, Ziegler et al., 1997, Scotese, 2002, 2004). Those paleotopographic reconstructions are mainly qualitatives, from the definition of three kinds of relief: low, middle and highlands (Smith et al., 1994, Ziegler et al., 1997), to semi-realistic images looking like shaded DEM (R.C. Blakey, http://jan.ucc.nau.edu/~rcb7, Scotese, 2004, www.scotese.com). Unfortunately the arguments on which are based those paleotopographic reconstructions are not discussed or corresponds to unknown "laws" of relief evolution from the present-day ones (Scotese, 2004). Defining a method of paleotopographic reconstruction is of primary importance.

Our project is based on new style paleogeographic maps with quantification of the land topography of the Earth for key periods of its evolution [Callovian, 165-161 Ma and/or Oxfordian, 161-155 Ma, Tithonian, 151-145 Ma, Valanginian, 140-136 Ma, Albian, 112-99 Ma, Cénomanian, 99-93 Ma, Maastrichtian, 70-65 Ma], with two steps (1) a semi-quantification (low, 0-50m, medium, 50-500m, high, 500-2000m, very high relief, >2000m) and (2) a true quantification (with decreasing resolution at increasing elevation) including slope estimates. For geologists, the first part implies a new approach where more than one century of geological knowledge has to be filtered to get the relevant data. Those data are merged into a single database and compiled using Geographic Information System (ArcGIS). This database will be free and available for all searchers at the end of this project. The second part requires an efficient collaboration with modellers of the lithosphere deformation and structural geologists. One of the challenge is to quantify uncertainities on those type of data.

A pilot study of paleotopography reconstruction has been carried out for the Cenomanian, key period of the Earth history. The image is very different from the present-day one. The only significative relief is the Laramian Mountain (North America). The Pacific subduction in South America only forms localised island arcs, as suggested by the marine flooding around these highs. The other significative relief is the collapse of the mountain belt (China, Mongolia, Russia) resulting from the Mongol-Okhotsk structure. A this time, the superimposed rifts are passing into SAGs.

The quantification of the past relief is based on the development of relief growth predictive laws depending on the geodynamic context (collision belt, rift, plateau…) and using (1) different boundary conditions controlling these relief (crust and lithosphere thickness, vertical displacement rate..) and (2) their consequences (type and spatial distribution of basins, siliciclastic sediment flux..).

We will briefly discussed on topography that does not exist in present-day environments: large subsident, preserved, continental domains, exoreic or endoreic. During Late Jurassic to Cretaceous times, these systems can be exoreic, connected to the sea (South Tethyan margin, Siberian border of the epicontinental marine Russian platform), endoreic, connected to large lakes (Congo "basin", Junggar, Tarim or extensional basins of NE China) or passing from endoreic to exoreic systems in response to ocean opening (Argentina margin, Amazon basin).

The quantification of the paleoelevation of the fluvial systems connected to the sea is based on the slope gradient ranges for each type of fluvial river (Smith et al., 1993; anastomosed: 10^{-5} to 10^{-4}, sinuous: 10^{-4} to 10^{-2}, braided 5×10^{-3} to 10^{-2}). The upstream elevation of a given type of fluvial river is estimated, started from the sea, on its length and on its slope. A pilot study has been successfully realised for the Barremian and Albian sediments of the South Tethyan margin.

Eustasy : signature of mantle processes ?

In their recent review, Miller et al. (2005) reasserted that long-term (>1 My) eustatic fluctuations are primarily (~100 m amplitude) controlled by the mean seafloor age (Hays and Pitman, 1973) and the oceanic lithosphere accretionary rates (e.g. Kominz, 1984; Larson, 1991; Berner, 1994). The volume occupied by sediments in the oceans and the volume of crust mobilized freed from the ocean and trapped into thickened crusts also contribute, but to a lesser extent (10s m amplitude). This is true in a static (as opposed to dynamic) Earth, and for a steady thermal regime. In the following, we suggest that the variations in sea level should instead be regarded as the product of (i) isostatic processes in a steady convective regime, (ii) isostatic processes in a transient convective regime, and (iii) dynamic processes, that exert a vertical traction beneath the surface of the Earth. In spite of Rowley's (2002) assertion that accretion rates remained constant for the last 180 Ma, Miller et al. (2005), based on eustatic observations, outlined that some eustatic variations have to be taken up by some other process, inferring variations in accretion rates. Conrad and Lithgow-Bertelloni (2007) and to a lesser extent, Cogné and Humler (2006) also came to the conclusion that seafloor production rates peaked during Lower Cretaceous. This part of our project aims at assessing the possible magnitude of competing controls on eustasy. This question is raised in the perspective of a dynamically consistent, i.e. assessing the significance of variations in the geometry (vertical and horizontal) of the oceanic basins in terms of internal dynamics of the Earth.