The African Plate (TAP): Lithosphere and Mantle Interactions and Implications for Basin Evolution: Preliminary insights into Regional Present-day and Paleo-stresses*

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Introduction

Initially part of Gondwana and Pangea, and now surrounded almost entirely by spreading centres, the African plate moved relatively slowly the last 200 million years. Yet both Africa's cratons and passive margins were affected by tectonic stresses developed at distant plate boundaries. Moreover, the African plate was partly underlain by hot mantle (at least for the last 300 Ma), as a series of hotspots or a superswell, or both - that contributed to episodic volcanism, basin-swell topography, and consequent sediment deposition, erosion, and structural deformation. The interaction between lithosphere and mantle is playing an important role in shaping and modifying the sedimentary basins and the related hydrocarbon accumulation, but a systematic analysis of timing and effect of all these key factors upon the African plate is presently lacking.

A detailed study that analyses the present day and evolution of main structural components of the African collage of plates and the tectonic forces that shaped the African continent has been undertaken by the Geological Survey of Norway and collaborators (University of Oslo, University of Trieste, University of Witwatersrand, and University of Liverpool) since 2008. The project is co-sponsored by Statoil ASA, Norway. The African Plate project is divided into several modules that aim to analyse the present-day structure of the African region crustal, lithospheric, and mantle structure, the location of continent-ocean boundaries and ages of oceanic crust by integrating existent data and knowledge in a comprehensive regional model. In addition, the kinematics of the main crustal components is reevaluated in the light of latest published models, new paleomagnetic data and available public-domain and industry geophysical data. A link between a new database of published geochronological data and location of onshore and offshore Cenozoic volcanism leads to possible clues on surface-deep mantle interactions.

This comprehensive knowledge base of the African region will be used to study several key questions linked to main tectonic events of Africa's geological history, such as: What is the connection between the predicted far-field stresses and recorded tectonic events in time and space?; Is Gondwana break-up linked to the rise of deep mantle plumes?; How did the mantle-lithosphere interactions shape Africa's sedimentary basins?

Stress Models

Present-Day Stresses

Quantifying present-day stresses is the first step in understanding the influences of structure of the lithosphere and the local, regional and possible global forces on the measured global stress (e.g., Bird et al., 2006; Humpreys and Coblentz, 2007) and has direct implications to petroleum exploration and production (e.g., Tingay et al.., 2005). As part of the African Plate project, the present-day stress for the region is modelled by considering and evaluating different models for the structure of the lithosphere, the contribution of the lateral variations of the density and rheology, and the influence of the mantle drag (Figure 1). The modelling of present-day stresses demonstrates the importance of ridge push, drag from the mantle flow, and variations of the crustal thickness, the main key players that shape the stress regime of plates. We also found that contributions of mantle lithosphere heterogeneities play a significant role in the state of isostasy and rheo logical variations of the African plate. The latter is chiefly attributed to variation of age-dependent crust properties and prompts us to explore how different geological provinces affect the state of stress.

Paleo-stresses

One step further is to model paleo-stresses through time in order to understand and assess the evolution of topography and basins. Models of paleo-stresses are being developed for selected time frames from the Jurassic to the present (Medvedev, in prep). These models aim to predict the orientations of the maximum horizontal compressive stresses developed in the African plate in the past and compare them to observations. Plate-tectonic reconstructions, the age distribution of the oceanic crust around Africa, mantle-flow models (Steinberger et al., 2010) and lithospheric heterogeneities supply the first order information for modelling the paleo stresses (see also Meijer and Wortel, 1999; Dyksterhuis et al., 2005). Plate- tectonic reconstructions use the latest regional and global models and understanding of the link between the motion of rigid plates relative to the convecting mantle and rising mantle plumes, and employ state-of-the-art public-domain (GPlates) and Statoil proprietary software (Splates and 4DLM) to develop regional models based on a wealth of geological and geophysical data (Figure 2). Complex modelling of stresses is performed by using the ProShell modelling software (developed at PGP centre at University of Oslo by S. Medvedev), the finite-element-based numerical suite that takes into account balances of in-plane stresses bending moments, and basal drag within the plates with variable thickness and curved geometry (see application of previous generation of ProShell in Medvedev et al., 2008). The paleo-stress models will be compared with published evidences for major changes in tectonic history of African margins and interior (e.g., Viola et al., 2005; Andreoli et al., 2009) and with new results from geological data collected in SW Africa (Namaqualand) that document changes in paleo-stresses from Paleozoic to present day (Viola et al., in prep). The results will further our understanding of the African continent, and can thus be used in hydrocarbon exploration for both understanding and predicting the evolution of petroleum-related African regions.

References

Andreoli, A., G. Viola, A. Kounov, J. Scheepers, O. Heidbach, and I. Stengel, 2009, History of stress at Vaalputs, Namaqualand, South Africa: Evidence for a Mid-Cretaceous “Wegener-type Orogeny” in western southern Africa: 11th SAGA Biennial Technical Meeting and Exhibition, Swaziland, Sept., 2009, p. 515-520

Bird, P., Z. Ben-Avraham, G. Schubert, M. Andreoli, and G. Viola, 2006, Patterns of stress and strain rate in southern Africa: Journal of Geophysical Research-Solid Earth, v. 111/B8, p. B08402. DOI: 10.1029/2005JB003882.

Dyksterhuis, S., R.D. Müller, and R.A. Albert, 2005, Paleostress field evolution of the Australian continent since the Eocene: Journal of Geophysical Research, v. 110/B5, 13 p.

Delvaux, D., and A. Barth, 2010, African stress pattern from formal inversion of focal mechanism data: Tectonophysics, v. 482, p. 105-128.

Humpreys, E., and D. Coblentz, 2007, North American dynamics and western U.S. tectonics: Review of Geophysics, v. 45, p. 3001-3031.

Medvedev, S., E.H. Hartz, and Y.Y. Podladchikov, 2008, Vertical motions of the fjord regions of central East Greenland: Impact of glacial erosion, deposition, and isostasy: Geology, v. 36, p. 539-542.

Meijer, P., and M.J.R. Wortel, 1999, Cenozoic dynamics of the African plate with emphasis on the Africa-Eurasia collision: Journal of Geophysical Research, v. 104, p. 7405-7418.

Steinberger, B, S.H. Buiter, S. Medvedev, and J. Tetreault, 2010, The mantle under Africa: An overview of global and regional tomography models, lithosphere thickness models and their effect on present-day and past dynamic topography: NGU internal report 2010.058.

Tingay, M., B. Müller, J. Reinecker, O. Heidbach, F. Wenzel, and P. Fleckenstein, 2005. Understanding tectonic stress in the oil patch: The World Stress Map Project. The Leading Edge, v. 24, p. 1276-1282.

Viola G., M. Andreoli, Z. Ben Avraham, I. Stengel, and M. Reshef, 2005, Offshore mud volcanoes and onland faulting in southwestern Africa: Neotectonic implications and constraints on the regional stress field: Earth and Planetary Science Letters, v. 231, p. 147-160.

Website

Heidbach, O., M. Tingay, A. Barth, J. Reinecker, D. Kurfess, and B. Müller, 2008, The World Stress Map database release 2008. Web accessed 30 August 2011, http://dc-app3-14.gfz-potsdam.de/

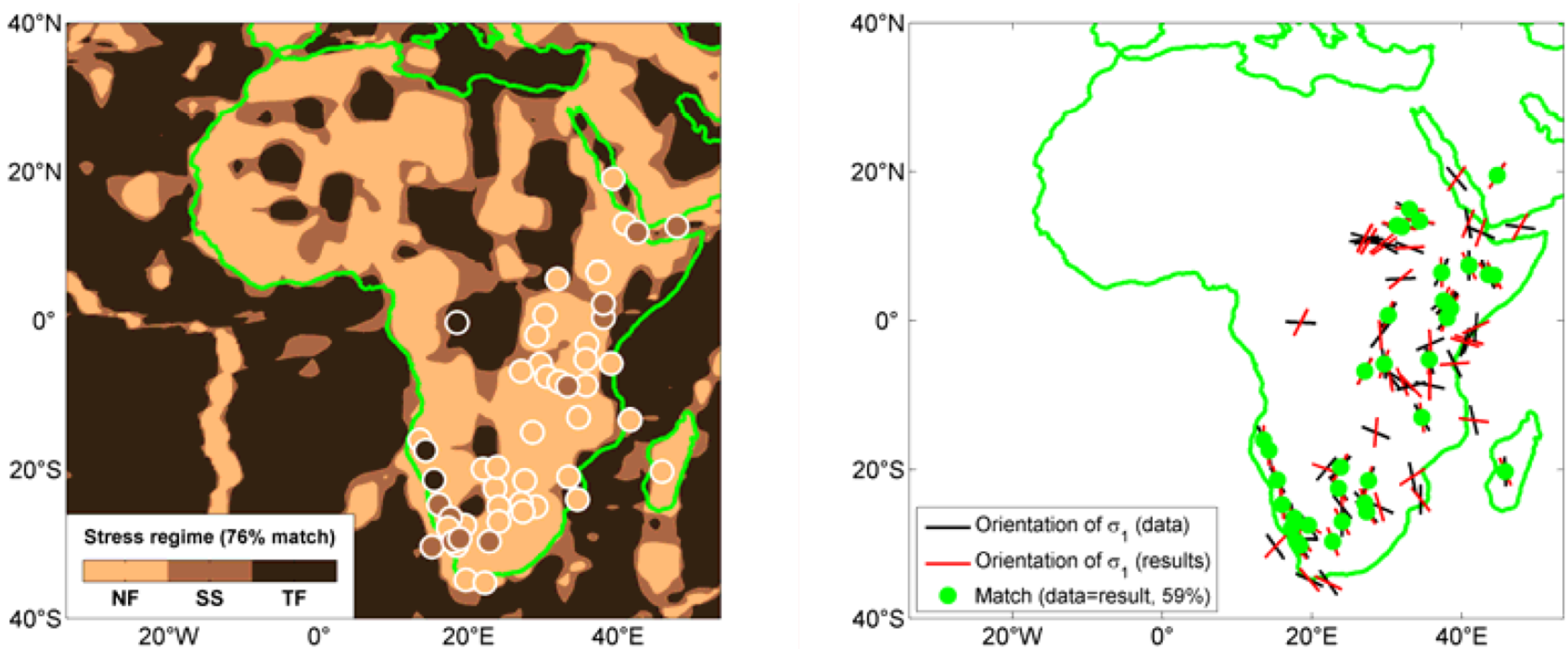

Figure 1. Illustration of calculated stress regimes (left) and orientation of maximal compressive stresses (marked as σ_1 on the right panel) compared to observations (Bird et al., 2006; Heidbach et al., 2008; Delvaux and Barth, 2010)-represented by coloured markers on the left panel. Green discs illustrate the results with orientation within 90% confidence interval of observations on the right panel.

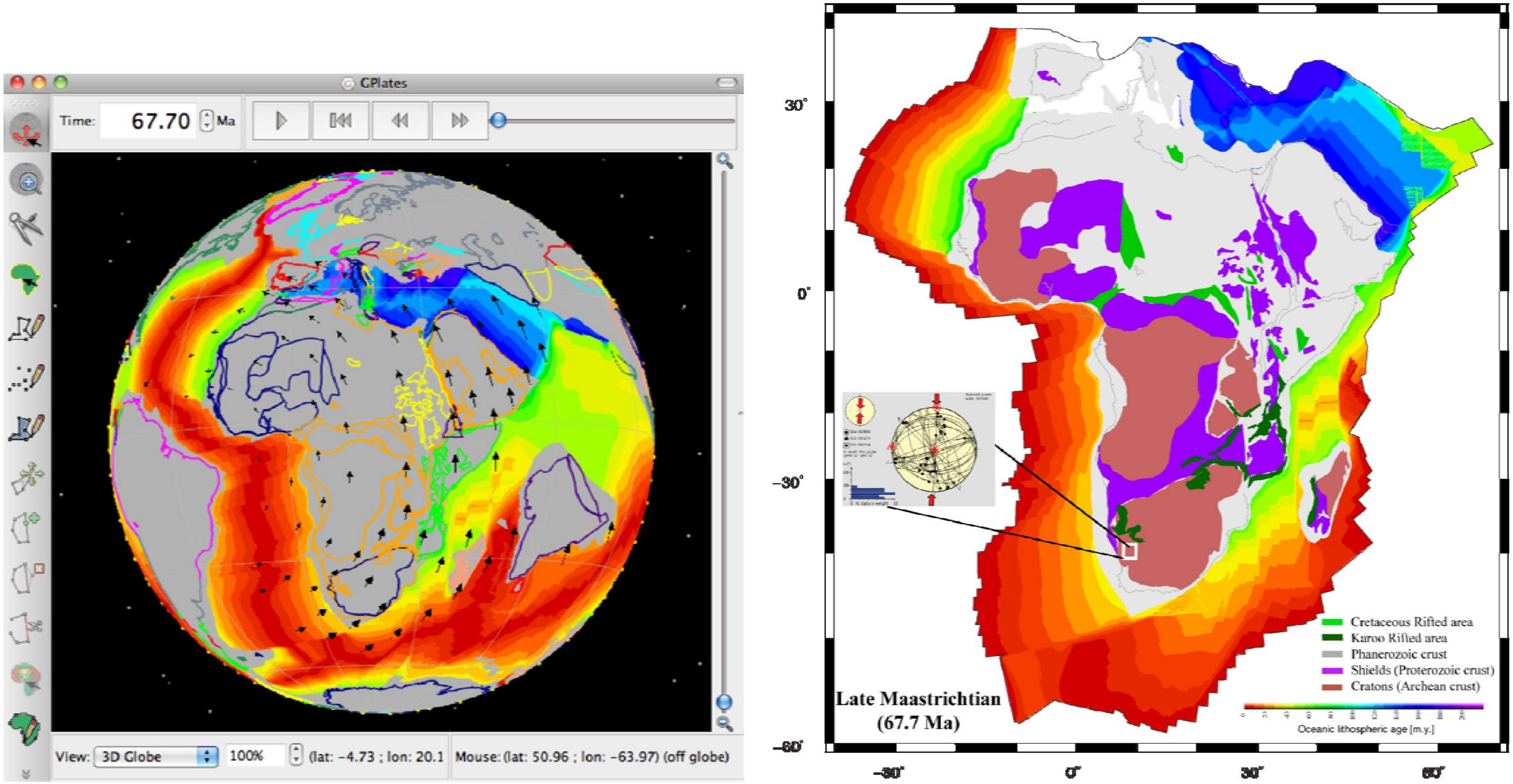

Figure 2. Left panel: Reconstructed age of oceanic floor and main continental blocks around the African plate at late Maastrichtian time (chron 31 time) using the GPlates software (www.gplates.org). Black arrows show the motion vectors of the African plate relative to the mantle.

Right panel: The African plate oceanic crust and main continental blocks to be used in modelling of paleo-stresses for Late Cretaceous time and preliminary stress inversion results using new structural data collected in Namaqualand, South Africa.