South Atlantic Margin Processes and Links with onshore Evolution*

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Introduction

Petroleum systems located at passive continental margins received increasing attention in the last decade mainly because of deep- and ultra-deep-water hydrocarbon exploration and production. The high risks associated with these settings originate mainly from the poor understanding of inherent geodynamic processes. The new priority program SAMPLE (South Atlantic Margin Processes and Links with onshore Evolution), established by the German Science Foundation in 2009 for a total duration of 6 years, addresses a number of open questions related to continental breakup and post-breakup evolution of passive continental margins. 27 sub-projects take advantage of the exceptional conditions of the South Atlantic as a prime "Geo-archive." The regional focus is set on the conjugate margins located east of Brazil and Argentina on one side and west of Angola, Namibia and South Africa on the other (Figure 1) as well as on the Walvis Ridge and the present-day hotspot of Tristan da Cunha. The economic relevance of the program is demonstrated by support from several petroleum companies, but the main goal is research on fundamental processes behind the evolution of passive continental margins.

How Do Continents Break Apart?

There is still debate on what causes rifting, whether it is an active process controlled by the mantle and in particular by plumes, or a passive response to broader plate reorganisations. Science teams addressing Mantle Dynamics and Magmatic Processes study the thermomechanical behavior of the mantle and related magmatic processes, which are key factors affecting the interplay of plate stresses, lithospheric strength, and surface response. True time-dependent models for mantle flow beneath the South Atlantic and Africa (Figure 2) are evaluated using observational constraints from global tomography, potential temperature, and composition of primary magmas, as well as dynamic-topography evolution and subsidence histories. Explicit incorporation of mineral-phase changes, melting topologies, and melt migration/flow laws permit numerical simulation of magmatic processes for different boundary conditions as potential temperature, thickness of lithosphere, and effects on uplift and subsidence through time. These models are backed up by a range of geochemical studies devoted to the assessment of the compositional diversity of magmas, the controls on melt productivity as well as time-space variations in magma flux and mantle temperature.

Post-Breakup Evolution

How rifts start and propagate in time and along strike is another fundamental question to address. The relative role of melting for weakening the lithosphere thermally and/or mechanically is juxtaposed to plate-tectonic effects of far-field stresses, or of pre-rift fabrics in the localization of the rifting process. The South Atlantic is the place to evaluate if there is a specific sequence of stretching, vertical movements, volcanism and new ocean formation, and how these processes vary along strike. Finally, the post-breakup evolution, the involved heat-flow history, sedimentation pattern and related consequences for resources are of interest. Therefore, studies in SAMPLE also address:
(1) the paleo- and present-day configuration of the sedimentary fill, the crust, and the lithospheric mantle in terms of geometry as well as of physical properties and,
(2) the implications for sedimentation and ocean circulation, for the heat flow and fate of deposited organic matter, and for feed-back with onshore evolution and climate.

The two conjugate margins are characterized by a pronounced asymmetry. Apart from the overall plate-tectonic setting this may be related to a strong structural inheritance of the pre-breakup lithosphere, but also to the relative position of different margin segments with respect to a mantle plume. To test which of these causes is the dominant controlling factor for the evolution of the individual segments, the structural-kinematic history of crustal-scale lineaments along the South Atlantic continental margins are studied based on detailed field-work on reactivation of basement faults as well as a fault-slip analysis to determine local paleo-stress states pre-, syn- and post-breakup. Hypotheses tested include different development following the extrusion of the Parána LIP’s (Large Igneous Province) in Brazil and the Etendeka LIP’s in Namibia, in response to hot-spot activities, influences by the Andean orogeny, and segmentation by large onshore fracture zones. Moreover, dynamic-topography evolution by thermochronology and thermokinematic 3D modelling will help to asses timing and rates of vertical movements and related variations in heat flow, sedimentation, and deposited organic matter. Quantifying the amount of crustal and lithospheric thinning and knowing the thickness evolution of sedimentary sequences through time and the distribution of magmatic products are required to properly assess rates of deformation. In these studies well data, seismic and seismological data available from industry and academic experiments, as well as the observed gravity and thermal fields, are integrated and complemented by newly acquired geophysical and geological data.

Starting in the north, a comparative analysis is carried out for the Late Cretaceous to recent post-breakup evolution of the Pelotas and Santos basins offshore southern Brazil and offshore Namibia and southern Angola. Studies that cover the southern portion of the conjugate system

focus on the Argentine and the Namibian-South African segments to assess the present-day state of the crust and lithosphere as well as the mechanisms and thermal consequences of subsidence and uplift. The deep structure of the crust and the presence of seaward-dipping reflector sequences and of high bodies as potential relicts of magmatic underplating are studied, based on existing seismic data to quantify the amount of emplaced volcanic/magmatic material as a function of the distance from the plume head. These results are integrated with potential field and heat flow data into 3D lithosphere-scale models imaging the structural, density, and temperature configuration (Figure 3) at present as the base for reconstructions of paleoscenarios. The post-rift tectonostratigraphic evolution and heat flow history are studied to:
(1) unravel the control factors on hydrocarbon generation, migration, and leakage, and
(2) assess the possible feedback between these processes and global climate through geologic time.
This involves seismo-stratigraphic interpretation and mapping of gas escape/sequestration features (mud volcanoes, carbonate mounds, seafloor pockmarks, gas chimneys, BSRs), complemented by high-resolution 3D petroleum system modelling and by field campaigns to the onshore equivalents of the offshore sequences.

The data-based studies are complemented by analogue as well as by thermo-mechanical modelling at both lithospheric and global scales. This will link the lithosphere with the deeper mantle to investigate the possible role of subduction zones around Gondwana as well as of global mantle convection, including the arrival of plumes generating tensile stresses in the continental lithosphere. The potential plume structures of the Tristan da Cunha hot spot are also addressed by new geophysical experiments where the Lithosphere of the Namibian Continental passive margin intersects with the Walvis Ridge.

Apart from deep mantle processes, regional stress fields, and structural inheritance, depositional processes at passive margins may additionally be influenced by regional ocean circulation pattern. To properly interpret the lithospheric signal in the sedimentary record, it is important to separate it from the oceanic signal. As the geometry of the Atlantic has experienced dramatic changes pre-, syn and post-breakup, different paleo-oceanographic signals are stored in the depositional record, resulting from different causes. To reconstruct and quantify depositional imprints related to (paleo-) oceanic currents, sediment drifts are studied and atmosphere-ocean circulation patterns are modelled for specific geological time slices by 3D simulations. The investigation of Eocene to Holocene sediment drifts focus on the Argentine Basin - an important path within the global conveyor belt- as it built up a long-term but high-resolution record of the oceanographic-climatic conditions. Their modifications may relate to plate-tectonic events such as the opening of the Drake Passage or the extensive emplacement of volcanic flows at the Rio Grande Rise/Walvis Ridge. Therefore analysis of the drift development will address the evolution of the water masses, the interaction of the currents with sediment input, and thus provide independent constraints for tectonic reconstructions and climate/ocean current simulations. The latter are based on 3D self-consistent global coupled atmosphere-ocean models for selected geological time slices and key tectonic events, such as the opening of the South Atlantic or the Drake Passage.

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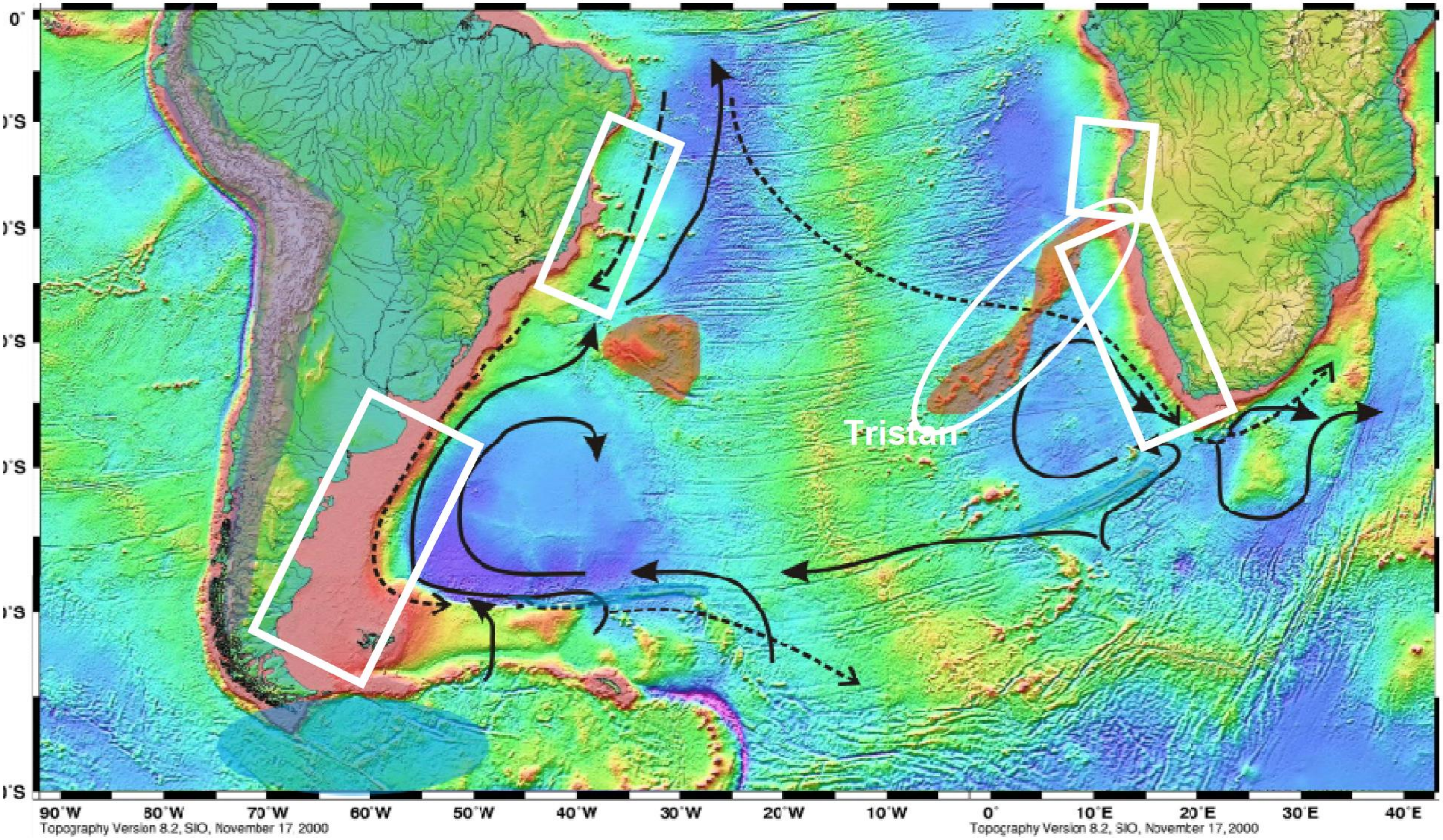

Figure 1. Bathymetry of the South Atlantic (Smith and Sandwell, 1997) with location of Tristan da Cunha hot spot. White rectangles: areas covered by studies in SAMPLE; white ellipse: area of new geophysical experiments; black arrows, solid lines: Antarctic Bottom Water; black arrows, stippled lines: North Atlantic Deep Water.

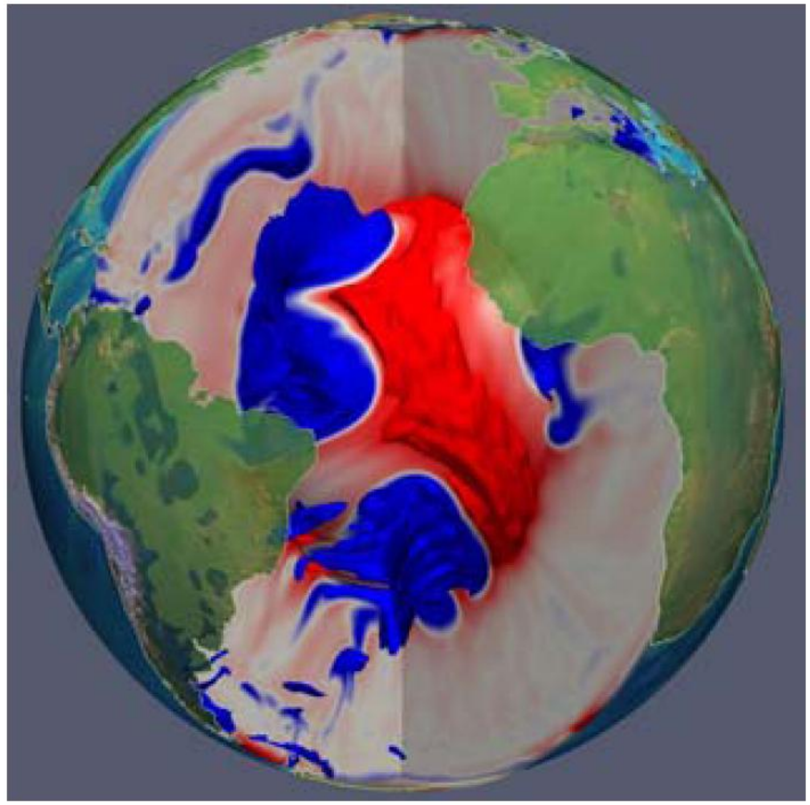

Figure 2. Example of a mantle flow model beneath the South Atlantic: red color: rising warm material, blue: colder domains, http://www.sample-spp.de/

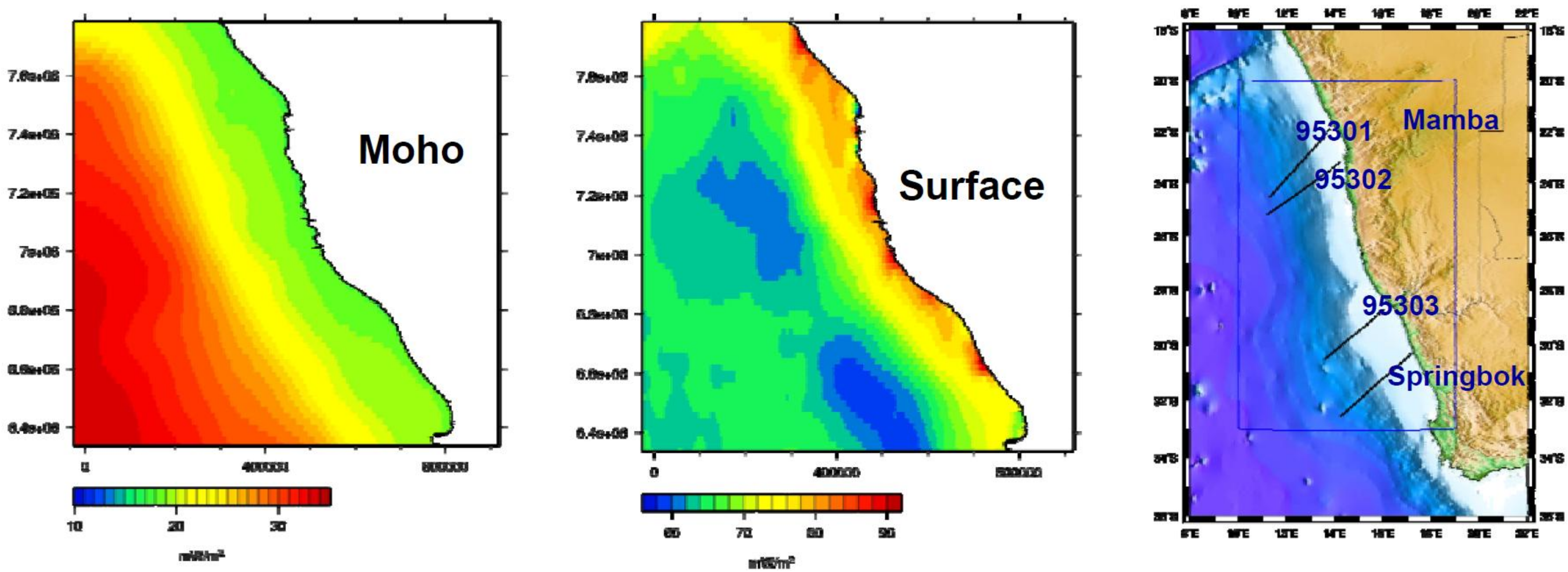

Figure 3. Present-day heat flow at Moho (left) and at surface (centre) predicted from a lithosphere-scale 3D model of the Orange Basin, South Africa (Hirsch et al., 2009). Location of modelled area (right), black lines: deep seismic refraction profiles (Bauer et al., 2000).