THERMAL TECTONIC FORWARD MODELLING IN THE SOUTHERN SOUTH ATLANTIC

Sebastian Hinsken[1], Anne Sofie Andersen[1], Hans Morten Bjørnseth[1] and Christopher Stadtler[1]

1: Equinor ASA Norway. sehi@equinor.com

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RESUMEN

El Océano Atlántico Sur (SA) es una región donde han sido probados en múltiples plays en diferentes cuencas. Este potencial ha sido evaluado en las partes central y norte, mientras que la parte sur del Atlántico Sur (SSA) ha experimentado una menor actividad de exploración y un éxito más limitado. En esta última región, a pesar de que existen claras evidencias de la acumulación de rocas generadoras de hidrocarburos, el estado térmico presente y pasado son poco conocidos, y por tanto el potencial relacionado con la madurez de las rocas generadoras también lo es. Con el objetivo de mejorar el conocimiento de esta incertidumbre y los consiguientes riesgos para la exploración de hidrocarburos, Equinor ha aplicado con éxito modelos termo-tectónicos directos en los márgenes del SSA. El modelado tectónico ha sido construido a partir de conocimientos regionales derivados de un detallado trabajo multi-disciplinario y ha sido aplicado en secciones regionales detalladas. El modelado térmico ha sido calibrado con los escasos datos de pozo disponibles, pero también con un análisis estadístico de flujos de calor superficiales. La integración de todos los datos disponibles a diferentes escalas, desde la tectónica de placas hasta las muestras de pozo, así como la evaluación de diferentes escenarios, ha incrementado el conocimiento y ha reducido el riesgo para definir áreas prospectivas favorables para la generación y acumulación de hidrocarburos.

INTRODUCTION

Giant petroleum accumulations have been discovered along the South Atlantic margins in recent years (e.g. Liza in Guyana, Tortue in Mauritania, SNE in Senegal, Brazil Pre-Salt, Venus and Graff in Namibia, etc.). The majority of these are located on the distal margins and in deep water making exploration and development extremely costly. The geology in these locations is often complex and poorly understood and has been strongly affected by the processes of continental breakup.

While most of the recent discoveries are located along the Transform Margins (e.g. Guyana in the Equatorial Atlantic) and in the passive margins in Central South Atlantic (Brazil, Gabon, Angola) the new discoveries offshore Namibia demonstrate the immense potential of the Southern South Atlantic (SSA) as large areas remain largely unexplored and un-tested to date. The key to unlocking the hidden potential is understanding the possible petroleum system, this requires a sophisticated petroleum system analysis involving high-quality basin modeling to identify sweet spots. A major restriction to petroleum system analysis in the SSA is the absence of wells in most of the area and therefore direct data concerning the thermal history and current thermal state of the basins are lacking. As an aim to solve this issue thermo tectonic forward modeling in the South Atlantic has been successfully tested and combined with traditional basin modeling. Together is forms the new integrated basin modeling workflow.

STUDY AREA

Integrated basin studies are presented in three areas: I) the Argentine Basin II) the African margin of the South Atlantic and III) the South Malvinas Basin (Fig. 1):

I. The Argentine Basin represents the western SSA passive margin (Kress *et al.* 2021). Rifting started in Jurassic and led to magma-rich continental break up during Early Cretaceous (ca. 130 ma). While the inner rift basins (i.e., Colorado Basin) have been explored to a limited extent, the distal margins remain unexplored.

II. The Orange, Luderitz and Walvis basins in South Africa and Namibia represent the conjugate margin to the Argentina Basin. Compared with the Argentina Basin the basins on the African margin are wider and the rift and break-up sequences are dominated by volcanics (McDermott *et al.* 2015). Very few wells have to date targeted the outer domains of these basins (Mello *et al.* 2019).

III. South Malvinas and Austral Basins formed by rifting during the Jurassic and have affinities to the formation of the Southern Ocean (Baristeas *et al.* 2013; Sachse *et al.* 2016). During the Cenozoic the southern parts experienced foreland basin development (Ghiglione *et al.* 2010). Onshore and near shore the Austral Basin (Jara *et al.* 2019) is a well explored oil province with a couple of discoveries in the near offshore (e.g., Carina Field). The offshore South Malvinas basin is however underexplored.

THERMAL TECTONIC FORWARD MODELING

Thermal tectonic forward modeling (TTFM) of sedimentary basins allows simulation of the thermal history in a realistic manner (Fig. 2). While it has been frequently used by academia, its application in basin modeling was limited, since it was difficult to reproduce the actual basin geometries. The chosen commercial forward modeling software, TecMod, combines thermal

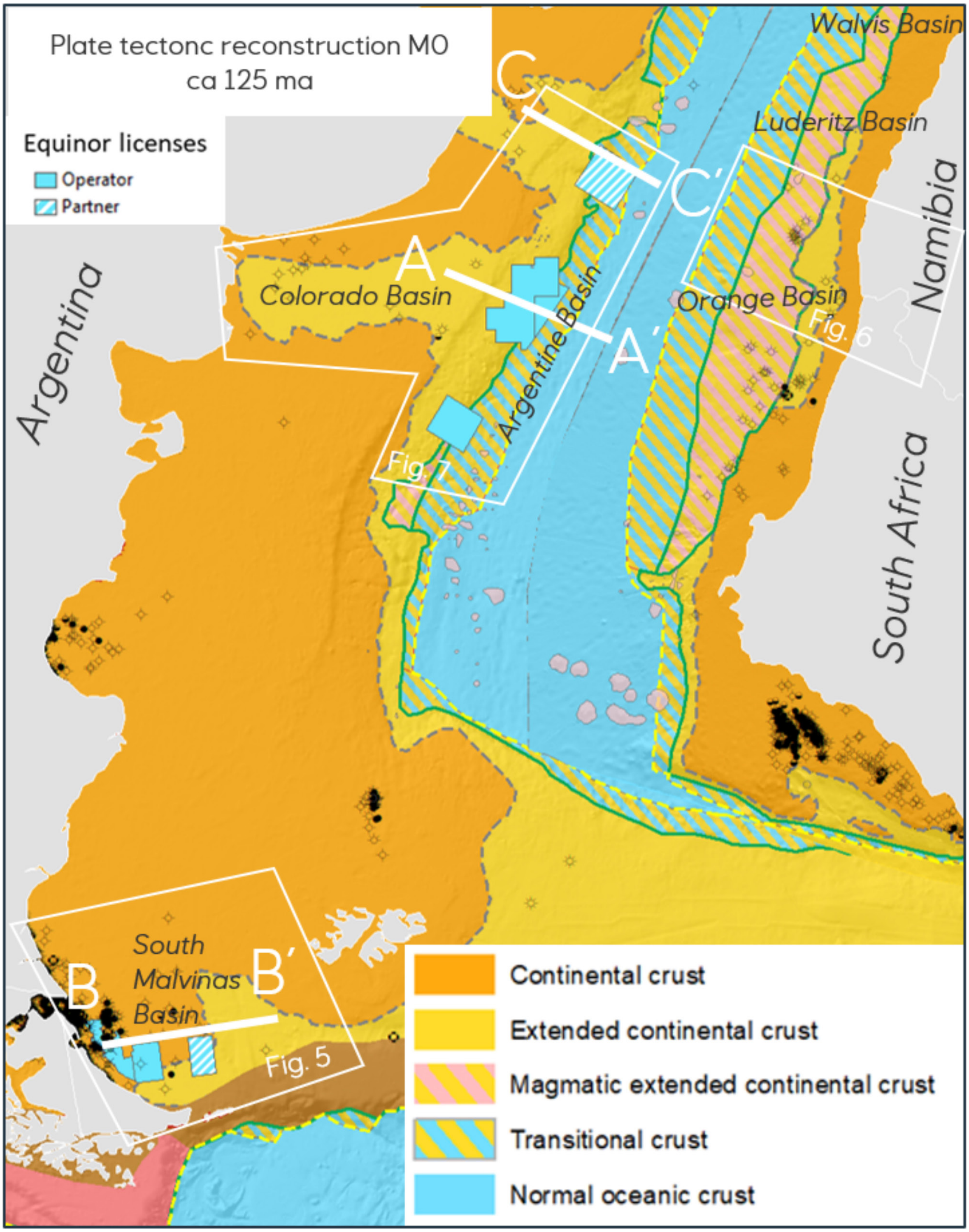

Figure 1. Reconstruction of Southern South Atlantic (SSA) during Early Cretaceous (Ca 125 Ma). Tectonic domains overlain by basin modeling areas, Equinor licenses and exploration wells (IHS). Tectonic Forward Modeling has been tested in the Argentine Basin, the conjugate African Margin (Orange, Luderitz and Valvis Basins) and in the South Malvinas Basin. Reference is given to figures (white polygons) and cross-sections (white).

tectonic forward modeling with basin inversion method and allows therefore to forward model - interpreted basin geometries (Rüpke *et al.* 2008). The finite element code simulates lithosphere scale conductive heat flow during extensional basin formation based on the thermal boundary conditions at top asthenosphere and the mudline. Therefore, the thermal conductivities, but also the heat capacity and the radiogenic heat production of the crust represent important modeling parameters that need to be carefully chosen. In addition, local superposing tectonic events like magmatism, salt tectonics and uplift and erosion can be modeled and their impact on the thermal history can be evaluated. Although modeling is limited to 2D the method is particularly applicable in areas with complex and/or controversial geological history and in very frontier settings like the SSA and provides realistic heat flow and paleobathymetry estimates that can be used for basin modeling.

In the following our integrated basin modeling workflow combining traditional basin modeling with thermal tectonic forward modeling will be presented, as well as providing some key examples of our work in the SSA.

WORKFLOW

The input basis for modeling are regional geological X-sections from seismic interpretation together with regional evaluations such as timing of tectonic events and paleogeography.

Thermal calibration is done using corrected well temperatures and vitrinite reflectance when available and in areas without well control the statistic mean of the surface heat flow has been used for calibration. A realistic estimation of the thermal conductivities and depth of the lithosphere asthenosphere boundary (LAB) are essential to obtain a reliable temperature prediction. The resulting modeled temperatures often show a very good correlation to corrected temperature measurements from wells (Fig. 3). Resulting heat flow maps from certain time steps are used as input to basin modelling. Scenario testing is an integral part of the workflow. It is often chosen when uncertainties persist in the geological interpretations or when modeling outcome mismatches the well data. Two examples of scenario testing are given, demonstrating the observation driven modeling approach:

Example 1) Thermal imbalance in the South Malvinas Basin (Carina field)

Figure 3 shows an E-W transect through the South Malvinas (East-Austral) Basin with projected well locations. Modeling of the section with rifting followed by foreland basin formation reproduced and matched the well temperatures encountered in the deep and central part of the basin. For the central part of the basin, a trend to slightly higher temperatures can be explained by a rise of the LAB towards the mainland.

Temperature gradients as high as 65°C/km are observed in the shallow areas around the Carina and neighboring fields on the Rio Chico High west of the South Malvinas Basin. Such high temperatures are difficult to explain with endogenous processes. In this shallow part of the basin a major erosional unconformity is seen at seabed and structural reconstruction indicate about 1 km of Pleistocene glacial uplift and erosion at the location of the Carina Field.

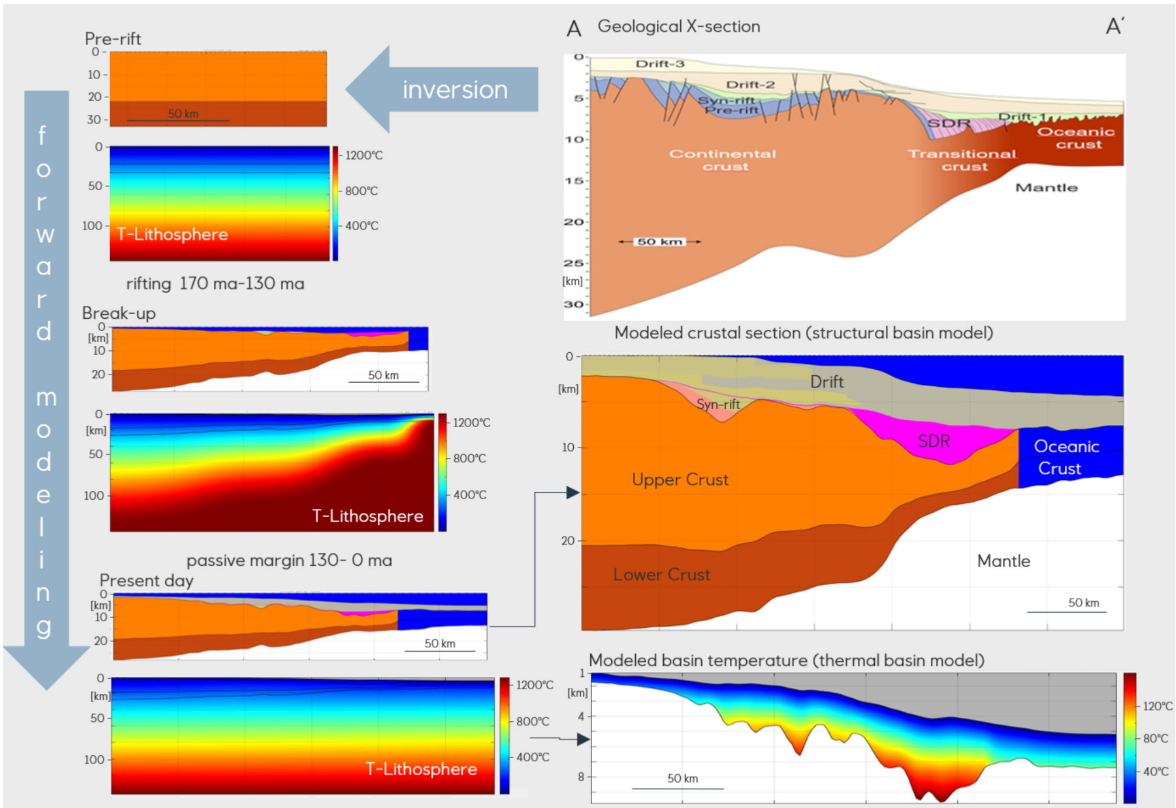

Figure 2. Example of tectonic forward modeling from the Argentine Basin (location on figure 1). 2D modeling is based on regional geological cross sections (upper right). Forward modeling procedure starting with undeformed crust and going through rifting, break-up, and passive margin stage (left). Restored crustal section is shown in comparison to lithosphere temperature profile. Modeled present-day basin and crustal geometry (centre right) and modeled basin temperature (lower right).

When modelling is done including uplift and erosion of 1 km between 1 Ma and 20 ka the results provide a good match with the measured temperatures and thus validate the scenario of sub-recent glacial uplift and erosion as an explanation to the high geothermal gradients in Carina. In addition, recent magmatic activity (Sachse *et al.* 2016) may have contributed to the elevated temperature gradients.

Example 2) Palaeo-Water Depth Modelling of the Argentine Basin

Another example of scenario testing shows the effect of melt generation and dynamic topography on paleo-water depth modelling at the Argentine Basin. Melt generation within the lithosphere has been identified as a process that can have a buoyant effect on the lithosphere during continental breakup and therefore result in shallower paleo-water depth (Quirk and Ruepke 2018).

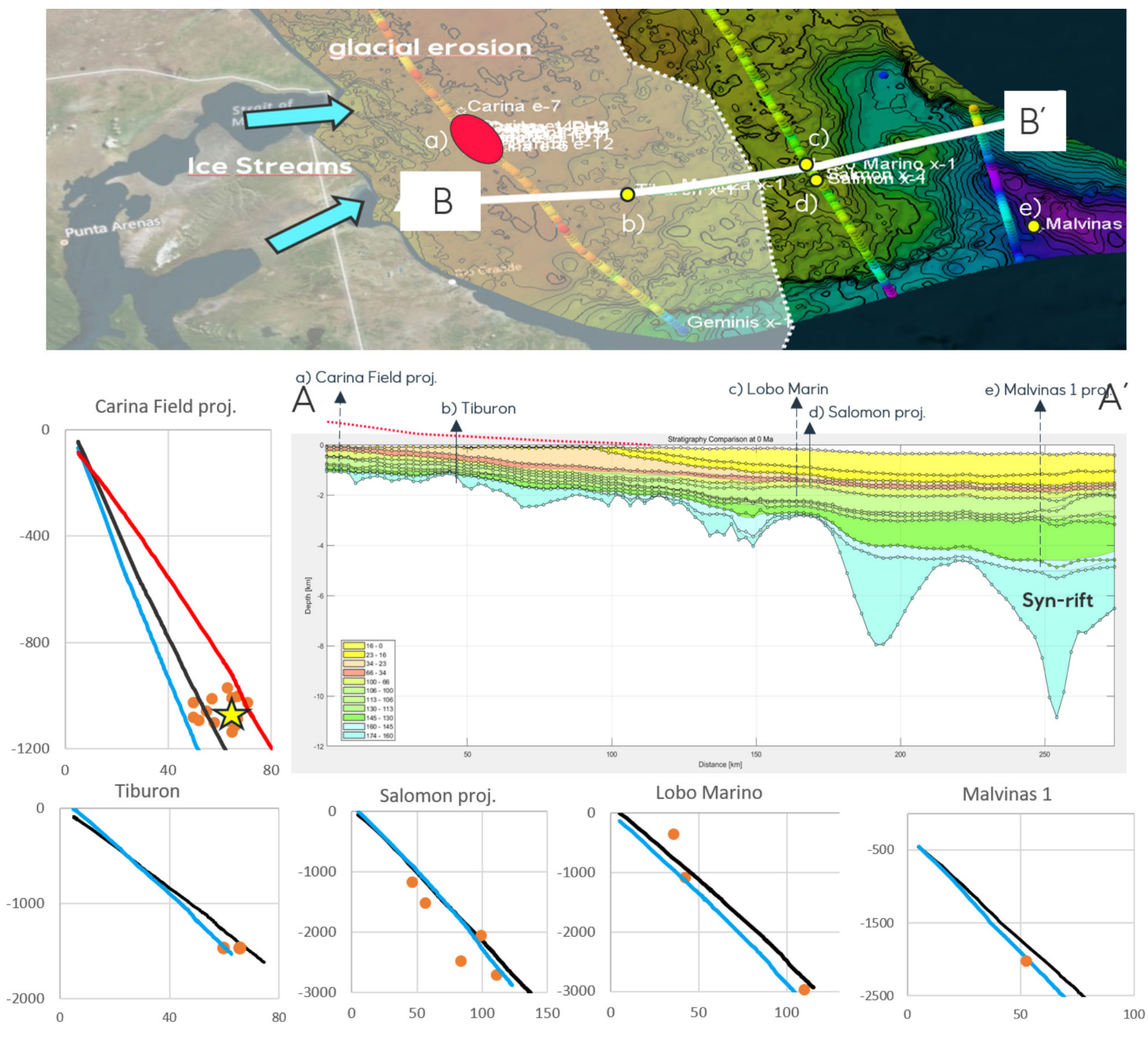

Figure 3. Example of thermal calibration and scenario testing of a 2D line B-B' modelled across the South Malvinas Basin. Modelled temperature gradients are compared to temperatures reported from wells (temperature/depth plots). Modelling with a lithosphere thickness of 150 km (black T-gradient) gives good results in the eastern part of the basin while 120 km (blue T-gradient) provides better results in the western part. High thermal gradients reported from Carina field (65°C/km) may be explained by glacial uplift and erosion (ca. 1 km between 1 Ma and 20 ka, red stippled line on section A-A') are considered (red gradient in Carina plot). Maximum glacial erosion for Carina Field is evident from location of the field adjacent to glacial valleys (e.g., Strait of Magellan).

Dynamic topography has been identified as a separate force resulting in uplift and subsidence at a scale of 2 km. This may interfere with thermal tectonic basin subsidence and can therefore have an additional impact on basin development. Regional subsidence that has affected the Argentinian slope in the Cenozoic is explained by dynamic topography in relation to emplacement of the subducted Andean slabs in the sub lithospheric mantle (Dávila *et al.* 2010).

Figure 4 shows 4 different modelled paleobathymetry scenarios (time vs bathymetry) for two locations on a line across the Argentinian Basin:

1. With Airy isostasy (blue line)
2. With dynamic topography correction (data from Flament *et al.* 2014, grey line)
3. Melt correction (yellow line)
4. Dynamic topography and melt correction (orange line)

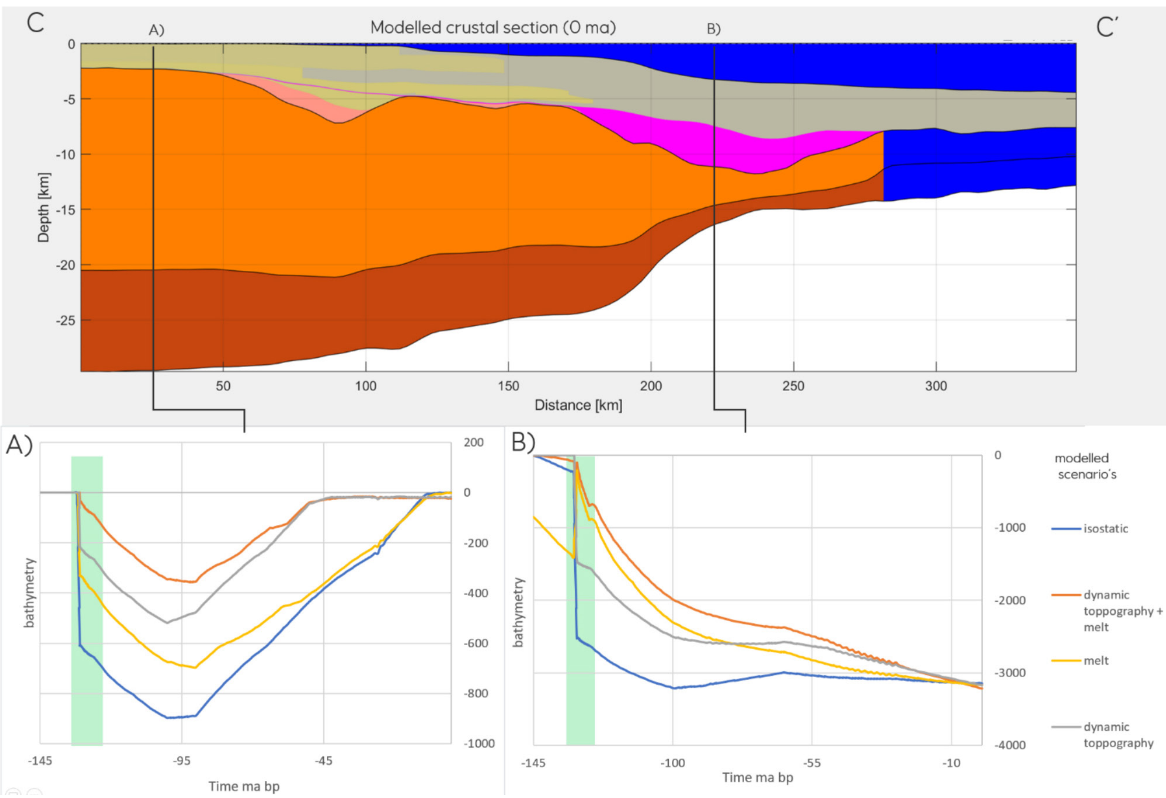

Figure 4. Paleobathymetry modelling on the Argentine Basin illustrated by two-time vs bathymetry plots (A, B) for the inner and outer domains (Line C-C'). Four scenarios integrating dynamic topography and melt generation have been tested. Modelling without correction (isostatic) overestimates paleobathymetry in reference to geological evidence. While dynamic topography has the largest impact on the inner domain (e.g., location A), melt generation (melt) drastically reduces modelled paleo bathymetry in the outer domains (e.g., location B). Combining melt and dynamic topography gives the most realistic paleobathymetry. Paleobathymetry interpretation is critical in -depositional models of source rocks. Anticipated source rock deposition interval is highlighted (green bar).

Melt correction puts SDR formation near or even at sealevel while dynamic topography result in realistic paleo-water depth estimates for the shelfal areas for this time interval.

The combined result gives a much better agreement with paleogeographic reconstructions than the uncorrected result and the obtained paleo-water / bathymetry depth can be used for basin modeling but also for predictions on depositional environments.

HEAT FLOW MAPPING AND INTEGRATED BASIN MODELING

The modeled basal heat flow and, in many cases, the paleo-water depth is area used as input for basin modeling. Heat flow maps are generated by combining modeled heat flow for certain time intervals from individual lines (Fig. 6). In many cases there is a linear relationship between heat flow and depth to top basement allowing for guided gridding of the 2D heat flow into heat flow maps.

The transfer of heat flow data to 3D basin modeling software is only applicable when both models use identical modeling parameters since changing the composition of the infill sediments during TTFM has direct effect on the modeled heat flow.

RESULTS AND APPLICATION

The predictive power of the integrated basin modelling workflow combining tectonic and basin modelling is demonstrated in an example from the conjugate Namibian margin (Fig. 6). There, the high impact discoveries of Venus and Graff in 2022 have been made in an area where

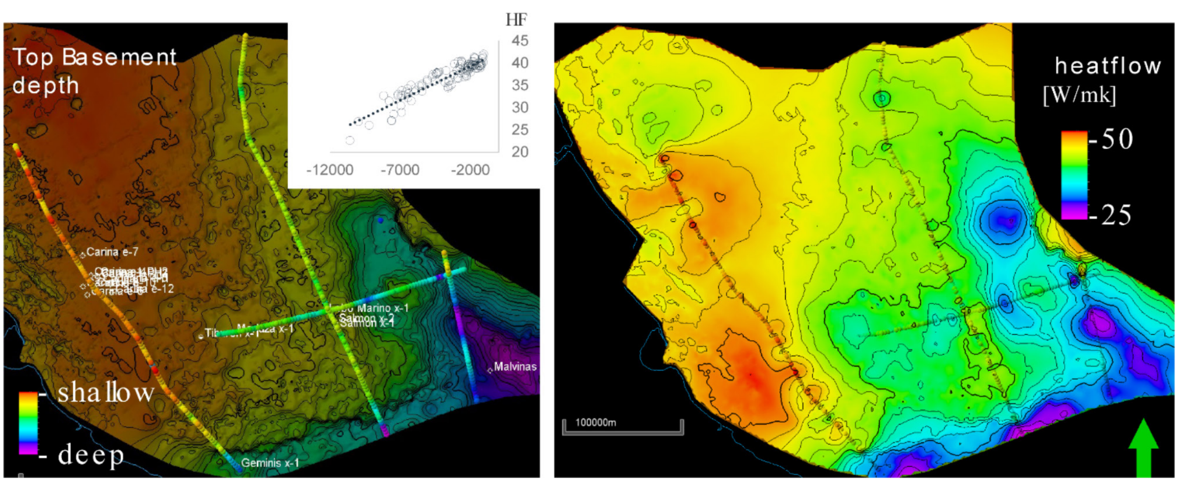

Figure 5. Example of heat flow mapping. Modelled heat flow values (present day, points) are overlain on top basement depth (left). A clear relationship is evident between Top Basement depth and modelled basal heat flow (diagram). Guided gridding with top basement gives therefore a realistic map of present-day basal heat flow that takes local variability as well as depth dependency into account.

Integrated Basin Modeling indicates present day oil and early gas generation from the Early Cretaceous source rocks.

On the Argentine and Colorado Basin (Fig. 8) where Equinor is currently holding acreage the Early Cretaceous source rocks are modeled to have reached the oil window in the Argentine Basin while in the adjoining Colorado Basin the anticipated source rocks have entered the gas window.

The results of Integrated Basin Modeling work combining thermal tectonic forward modeling with traditional basin modeling have provided confidence in our ability to identify prospective areas for hydrocarbon generation, and results suggest that both the Argentine and conjugate African Basins as well as the South Malvinas/ E. Austral Basins contain such favorable areas.

SUMMARY AND CONCLUSIONS

The Southern South Atlantic (SSA) is a very promising but also complex frontier exploration area. A major key to success will be the most accurate evaluation of the petroleum systems. This

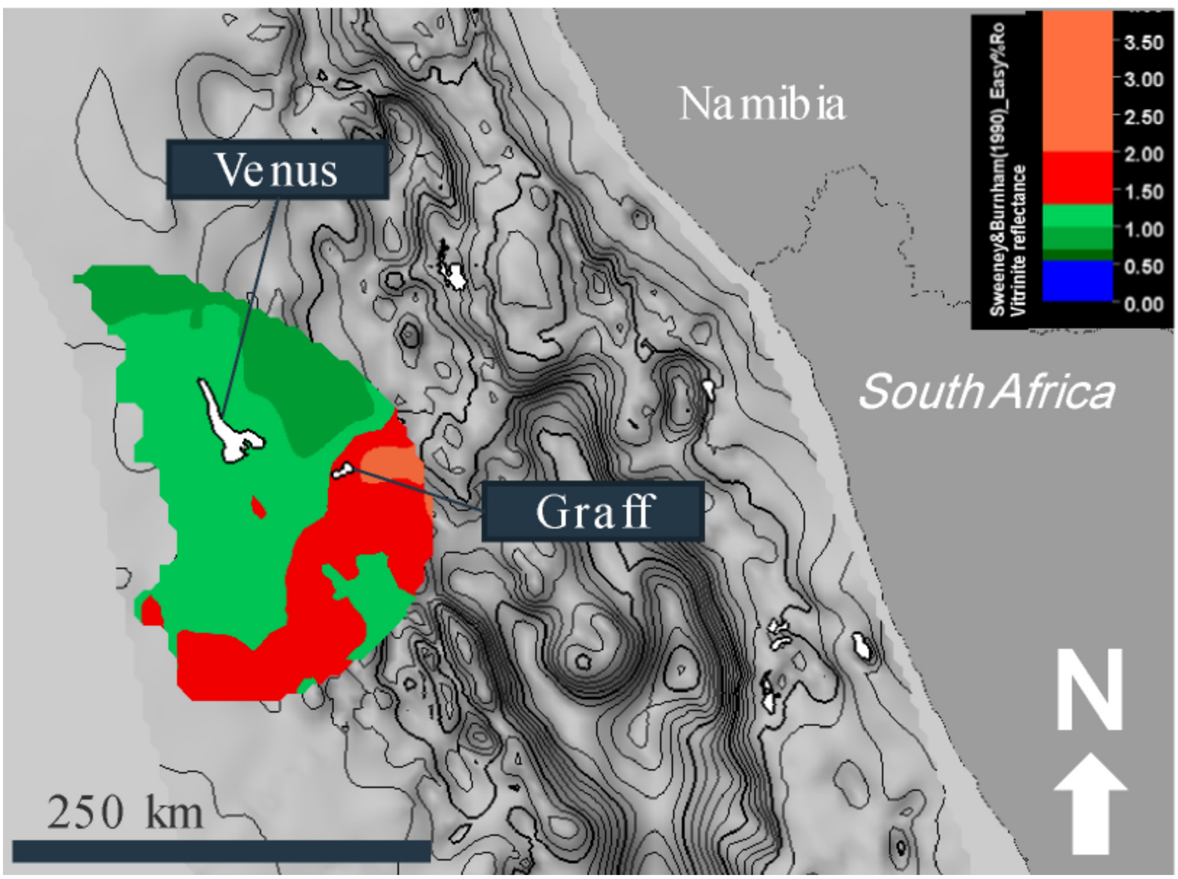

Figure 6. Modelled Present day vitrinite reflectance (Easy Ro%) on structural map for the E Cretaceous source rocks around the giant Venus and Graff discoveries. Modelled source rock maturity fits well with the encountered hydrocabon phase.

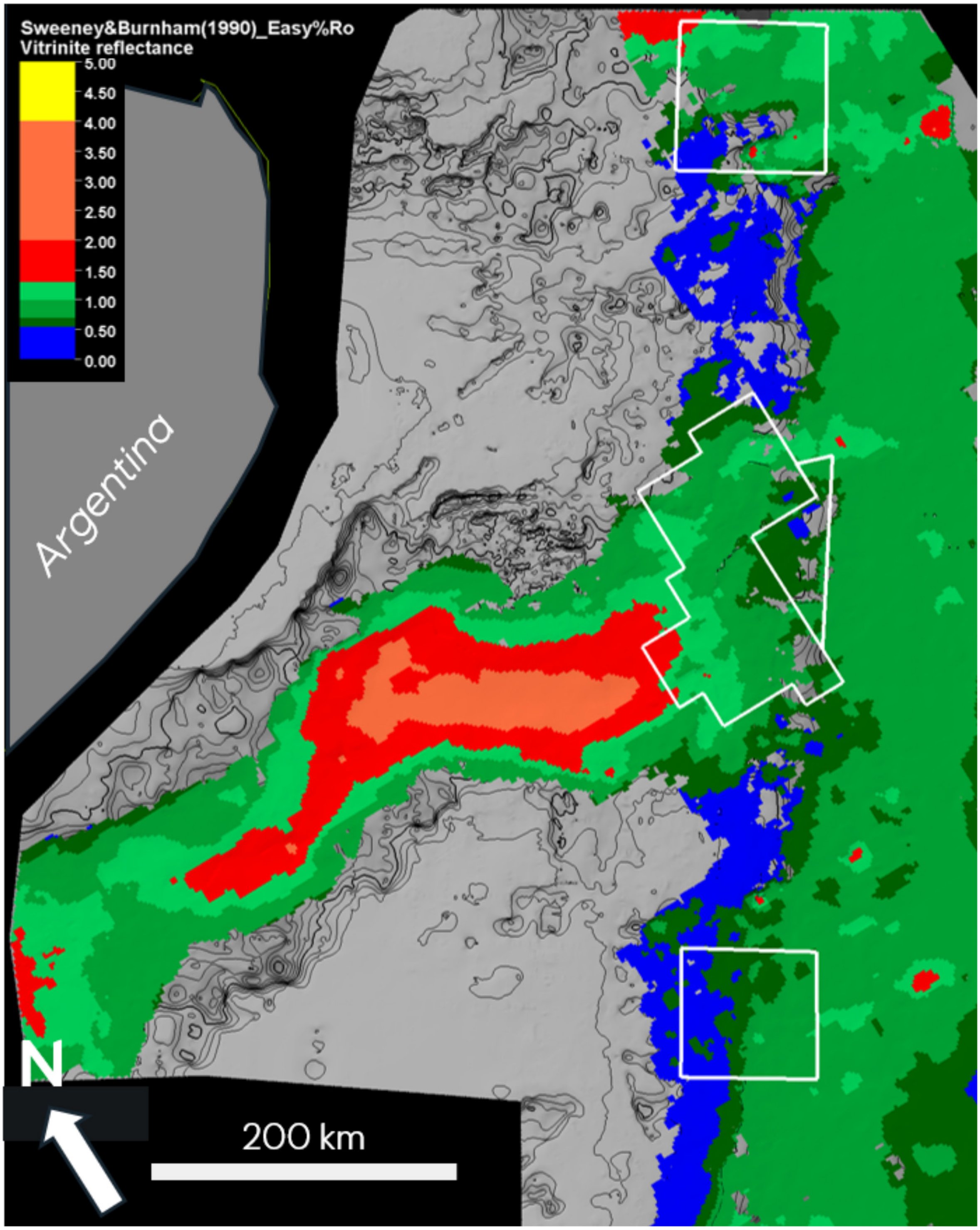

Figure 7. Modeled present-day vitrinite reflectance (Easy Ro%) of the anticipated Early Cretaceous SR rocks on structural map in the Argentinian Basin where Equinor holds licenses (white outlines). Oil maturity is seen along the passive margin while gas maturity is predicted for the Colorado Basin.

study shows that implementing tectonic forward modelling in an integrated basin modelling workflow can help improve the identification of areas located in such favorable settings for hydrocarbon generation.

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