Controls on Natural Gas Seepage and Focused Fluid Flow on the South Atlantic and the Barents Sea*

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Search and Discovery Article #40803 (2011)
Posted September 12, 2011

*Adapted from article published in AAPG European Region Newsletter, June 2011 (http://europe.aapg.org/wp-content/uploads/2011/03/AAPG_Newsletter-June-2011_final_fixed2.pdf). Appreciation is expressed to AAPG European Region Council, Jeremy Richardson, Director, David R. Cook, President, and their Editorial Board, Karen Wagner, Chief Editor.

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Introduction

Leakage of liquid and gaseous hydrocarbons through focused fluid flow systems is a process recognised in most sedimentary basins and on continental margins. Studying the abundance, distribution and drivers for this process is crucial to understand its role on geological phenomena, such as submarine slope stability and gas hydrate dynamics. Additionally, since natural gas seepage is a source to the ocean and atmosphere of powerful greenhouse gases, such as methane, it might have played a role on world's ocean chemistry and Earth's past maximum-thermal events. Moreover, as this process is usually associated with distribution of subsurface hydrocarbon accumulations, it has a clearly significant economic importance.

Gas chimneys, mud volcanoes, seabed pockmarks, and carbonate mounds have been recognised to be indicators of active natural gas migration and leakage from deeper sources and reservoirs (e.g., Anka et al., 2009; Berndt, 2005; Gay et al., 2007; Hornbach et al., 2007; Hovland and Judd, 1988; Leon et al., 2006; Loncke et al., 2004; Orange et al., 2002). Recognition of similar buried features could indicate the occurrence of comparable events staggered through time, which may be triggered by sea-level changes, uplift and erosions, regional and local tectonics, and/or glacial cycles. Although great deal of work has been performed on the identification and description of these indicators along continental margins (i.e. Berndt, 2005; Gay et al., 2007; Hornbach et al., 2007; Hovland and Judd, 1988; Leon et al., 2006; Orange et al., 1999), the deeper hydrocarbon systems that feed the seeps are seldom addressed, much less the thermogenic-gas fluxes quantified. Thus, a real mass balance of the global amounts of thermally generated methane emissions and their temporal variability is yet to be investigated. A detailed study is currently being undertaken in this sense by a recently created Helmholtz-University Young Investigator Group at the Organic Geochemistry Section of the GFZ German Research Centre for Geosciences (Helmholtz Center Potsdam).The group is co-sponsored by the

Helmholtz Association of German Research Centers and the Technical University of Berlin (TU Berlin). Several data-exchange agreements with industry partners provide access to seismic reflection and well data.

Our study aims at a comprehensive understanding of the driving mechanisms of hydrocarbon seepage and thermogenic-gas fluxes by means of process-oriented models, both at basin and super-regional scales. Reconstruction of the volumes and rates of thermally generated methane emissions to the hydrosphere and atmosphere should provide insights on the possible feedback between this process and global palaeo-climate. Our Results complement previous studies developed at the GFZ's Organic Geochemistry section and are instrumental in GFZ's larger research initiative "Methane on the Move" (MoM) , which deals with a global assessment of the fate of thermogenic and biogenic methane in marine and terrestrial systems over geologic time on a planetary scale.

The study is structured into a series of projects carried out on several of natural laboratories:

The Argentinean Continental Margin

The Colorado and the Malvinas basins are two of the sedimentary basins developed on offshore Argentina's rifted margin and separated by a series of basement ridges oriented ENE-WSW and ESE-WNW (Figure 1). The Colorado basin is an E-W-trending graben developed perpendicular to the margin with an area of about 130000 km². Its eastern boundary is a basement high parallel to the margin and separating the basin from the deep-oceanic Argentine Basin. Three main post-rift depocenters have been identified; the deepest one contains up to 15 km of sediments, of which about 7km would be Albian-Maastrichtian. The Malvinas basin is located between Tierra del Fuego and the Malvinas islands, with a NNW-SSE elongated shape (350 x 150 km) and a sedimentary filling ranging from 2 to 8 km. The basin is developed entirely within a wide continental shelf and is surrounded by Paleozoic pre-rift terrains, except to the south where it ends abruptly against the Burdwood Bank and the north Scotia Ridge (Galeazzi, 1996; Yrigoyen, 1989).

Interestingly enough, this part of the Argentinean margin has been shaped by the interaction between South America, Antarctica and Scotia plates. The conjugated basins of the Colorado and Malvinas are thought to be the South African Orange and the Bredasdorp basins, respectively (Lawver et al., 1998; Unternehr et al., 1988). Oil and gas recovered from Lower Cretaceous intervals and minor oil shows from Paleogene and Miocene sections in the Malvinas basin (Galeazzi, 1998) as well as recovered oil/gas samples and rock-extracted bitumen in a few exploration wells in the Colorado basin indicate the existence of favourable conditions for the deposition and thermal maturation of source rocks, as well as the existence of petroleum systems in both basins (Katz and Mello, 2000; Szatmari, 2000; Vayssaire et al., 2007).

The first phase of these projects consists on the reconstruction of the post-rift tectono-stratigraphic evolution of both basins, understanding the possible structural or stratigraphic control on leakage events. These tasks involve seismo-stratigraphic interpretation and detailed mapping of past and present-day of gas escape or sequestration features (Figure 2a).

The second phase focuses on the quantification of the thermogenic emissions through time, which is achieved through high-resolution 3D petroleum system modelling (Figure 2b). Resulting Map-based models of drainage areas and closures are then calibrated with the mapped expressions of leakage. In addition, a sampling campaign was recently carried out to the immature onshore equivalents of the main source rock intervals for further geochemical analysis.

The Southwestern Barents Sea, Hammerfest Basin

This is a frontier area for fossil resources exploration and an excellent setting for scientific research due to the complex environment and the various interactions among the rift, the continent, the ice, and liquid and gas hydrocarbons. The juxtaposition of the North Atlantic volcanic rifted margin with the distinct borderland of the Barents Sea makes for an unusual Meso-Cenozoic tectono-sedimentary history (Figure 1). In addition, petroleum systems in the region are highly sensitive to thermal and tectonic changes, and these systems have been strongly influenced by the extraordinary Pleistocene glacial activity. It is widely accepted that uplift and erosion occurred over an area including Svalbard, the Barents Sea, Scandinavia and the British Isles. The Norwegian mainland experienced up to 1000 m of uplift, and an excess of 3000 m of uplift occurred on the northern part of the Barents Shelf (see compilation of amount and timing in Cavanagh et al., 2006)). In general, there are three main episodes of exhumation for the southwestern Barents Sea: (1) Late Palaeocene uplift and related igneous activity (55–50 Ma) prior to the onset of crustal break-up and North Atlantic rifting; (2) Oligocene–Miocene inversion (30–15 Ma) and widespread occurrence of shallow-marine conditions associated with passive margin development as rifting moved farther north; (3) Late Pliocene–Pleistocene erosion (2.5–0 Ma) of the shelf area associated with ice sheet scouring and large submarine fan deposits west of the shelf break.

The aim of this project is to elucidate the effects of tectonic uplift, glacial loading, and post-glacial rebound and erosion, on the timing and extent of hydrocarbon gas sequestration in hydrates and their possible dissociation during the interglacials of the Quaternary Ice Age. Previous 2D calibrated models indicate that ice loading and removal during glacial and interglacial events have a profound influence on the hydrocarbon accumulations, and a significant present-day thermal disequilibrium in the Hammerfest Basin results from Late Cenozoic exhumation (Cavanagh et al., 2006).

Extrapolation of Weichselian ice sheet oscillations indicates that about forty of these cycles would have taken place over the last 1 Ma. Preliminary results from this project indicate that such fluctuations provide a mechanism for the (i) episodic discharge of large quantities of thermogenic methane from the deep petroleum system, (ii) sequestration of this gas as clathrate, (iii) subsequent hydrate decay and sudden release of important volumes of methane to the seafloor right after the Last Glacial Maximum (Ostanin et al., 2011; Rodrigues et al., 2011) (Figure 3).

Super-Regional Integration of the South Atlantic

The aim of this project is to compile and integrate the results from our past and current work carried out in individual basins of the South Atlantic, in order to build a regional database containing the distribution of main post-rift depositional sequences and sequence boundaries, sedimentation rates and deposited volumes, timing of major tectonic pulses, source-rock distribution, heat flow, and recognised hydrocarbon leakage expressions. Particular interest is placed in elucidating the chronological correlation between regional tectonic/erosional events, large slumps / mass transport deposits, submarine currents / sea-level fluctuations, and the identified massive gas release episodes. This compilation will provide a super-regional perspective on the driving mechanisms of generation, migration, sequestration, and leakage of natural gas during the Cenozoic post-rift history of the South Atlantic. Due to the large-scale nature of the project, it is necessary for the implementation or adaptation of new methodologies that allow to quality check, simplify, and reduce the amount of input data into the petroleum system model, while the outputs remain significant at the regional scale. The methodological approach will be validated by calibration with the 3D high-resolution models developed in each individual basin from the individual projects. The project is developed in closed collaboration with the SAMPLE initiative established by the German Science Foundation (DFG) already referenced in this newsletter (see AAPG – European Region Newsletter Vol 5. September 2010).

Selected References

Anka, Z., R. Ondrak, and L.F. Clausen, 2009, Modelling hydrocarbon generation, migration and present-day hydrocarbon seepage from the deep offshore slope of Angola: Search and Discovery Article #90090. Web accessed 25 August 2011. http://www.searchanddiscovery.com/abstracts/html/2009/annual/abstracts/anka.htm

Berndt, C., 2005, Focused fluid flow on continental margins: Philosophical Transactions of the Royal Society Series, v. A/363, p. 2855-2871.

Cavanagh, A., R. diPrimio, M. Scheck-Wenderoth, and B. Horsfield, B., 2006, Severity and timing of Cenozoic exhumation in the southwestern Barents sea. Journal of the Geological Society, v. 163/5, p. 761-774.

Galeazzi, J.S., 1998, Structural and stratigraphic evolution of the western Malvinas Basin, Argentina: AAPG Bulletin, v. 82/4, p. 596-636.

Gay, A., Lopez, M., Berndt, C. & Séranne, M. 2007: Geological controls on focused fluid flow associated with seafloor seeps in the Lower Congo Basin. Marine Geology 244, 68-92.

Lopez, M., C. Berndt, and M. Séranne, 2007, Geological controls on focused fluid flow associated with seafloor seeps in the Lower Congo Basin: Marine Geology, v. 244, p. 68-92.

Hornbach, M.J., C. Ruppel, and C.L. Van Dover, 2007, Three-dimensional structure of fluid conduits sustaining an active deep marine cold seep: Geophysical Research Letters, v. 34/L5601, 5 p.

Hovland, M., and J. Judd, 1988, Seabed Pockmarks and Seepages: Impact on Geology, Biology and Marine Environment: Graham and Trorman, London, 293 p.

Katz, M., and M. Mello, 2000, Petroleum system of South Atlantic marginal basins: An overview: AAPG Memoir, v. 73, p. 1-13.

Leon, R., L. Somoza, T. Medialdea, A. Maestro, V. Diaz-Del-Rio, and M.C. Fernandez-Puga, 2006, Classification of sea-floor features associated with methane seeps along the Gulf of Cadiz continental margin: Deep-Sea Research v. II/53, p. 1464-1481.

Loegering, M.J., Z. Anka, J. Autin , R. di Primio, D. Marchal, J.F. Rodriguez, and E. L. Vallejo, (in press), Seismo-stratigraphy, tectonic evolution, and hydrocarbon leakage indicators in the Colorado Basin, offshore Argentina, South America: Tectonophysics.

Loncke, L., J. Mascle, and F.S. Parties, 2004, Mud volcanoes, gas chimneys, pockmarks and mounds in the Nile deep-sea fan (Eastern Mediterranean): geophysical evidences: Marine and Petroleum Geology, v. 21/6, p. 669-689.

Orange, D.L., H.G. Greene, D. Reed, J.B. Martin, C.M. McHugh, W.B.F. Ryan, N. Maher, D. Stakes, and J. Barry, 1999, Widespread fluid expulsion on a translational continental margin: Mud volcanoes, fault zones, headless canyons, and organic-rich substrate in Monterey Bay, California: GSA Bulletin, v. 111/7, p. 992-1009.

Ostanin, I., Z. Anka, R. Di Primio, J.E. Skeie, and A. Bermal, 2011, Analysis of fluid migration and leakage in the Hammerfest Basin, South Western Barents Sea, from 3D seismic reflection data: EGU General Assembly 2011: Geophysical Research Abstracts, v. 13, EGU2011-488, Vienna, Austria.

Rodrigues, E., R. di Primio, Z. Anka, D. Stoddart, and B. Horsfield, 2011, Leakage of hydrocarbons in a glacially influenced marine environment: Hammerfest Basin (Southwestern Barents Sea.): Geophysical Research Abstracts, v. 13, EGU2011-765.

Szatmari, P., 2000, Habitat of petroleum along the South Atlantic margins: AAPG Memoir, v. 73, p. 69-75.

Unternehr, P., D. Curie, J.L. Olivet, J. Goslin, and P. Beuzart, 1988, South Atlantic fits and intraplate boundaries in Africa and South America: Tectonophysics, v. 155, p. 169-179.

Yrigoyen, M.R., 1989, Cuenca de Malvinas, *in* G. Chebli, and L. Spaletti, (eds.),Cuencas Sedimentarias Argentinas: Serie Correlación Geológica: Correlación Geológica, p. 481-491.

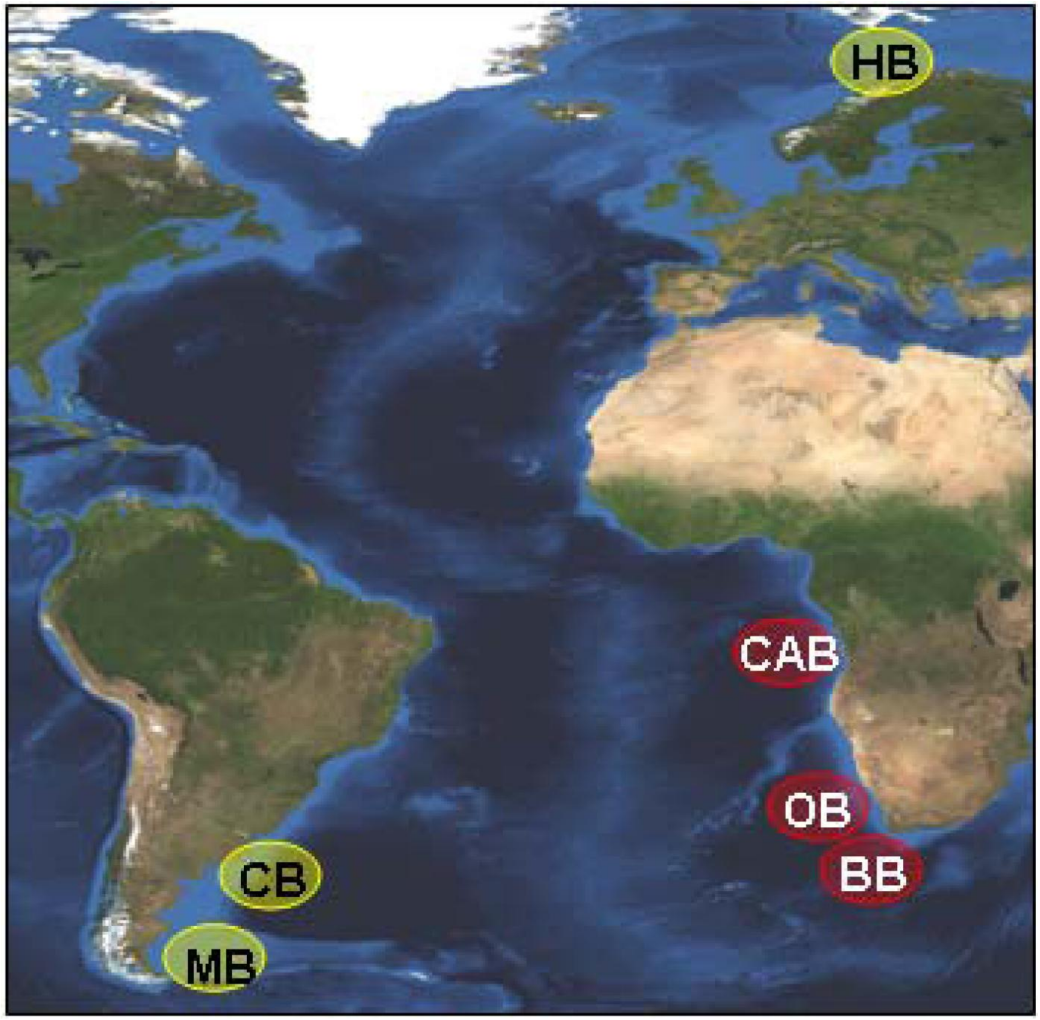

Figure 1. Location map of the basins currently being studied. (yellow circles) and study areas from previous works. (MB: Malvinas Basin, CB: Colorado Basin, HB: Hammerfest Basin, CAB: Congo-Angola Basin, OB: Orange Basin, BB: Bredasdorp Basin).

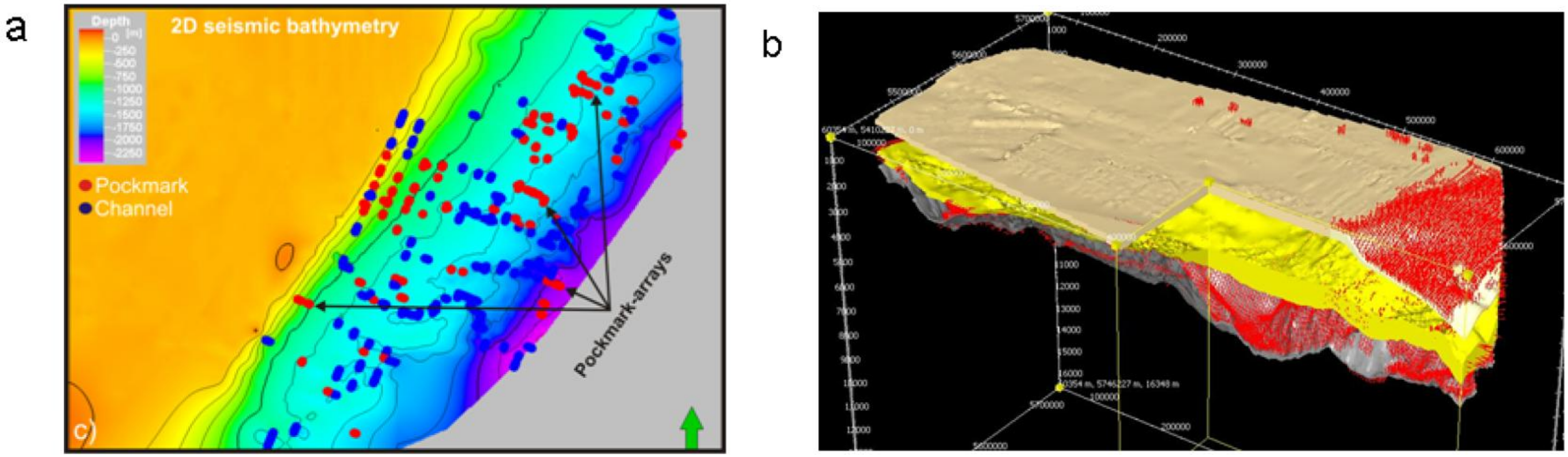

Figure 2. (a) Distribution of present-day gas chimneys and seabed pockmarks on the slope of the Colorado Basin. (b) 3D model of migration paths calibrated to the observed leakage features (Lögering et al., submitted to Tectonophysics).

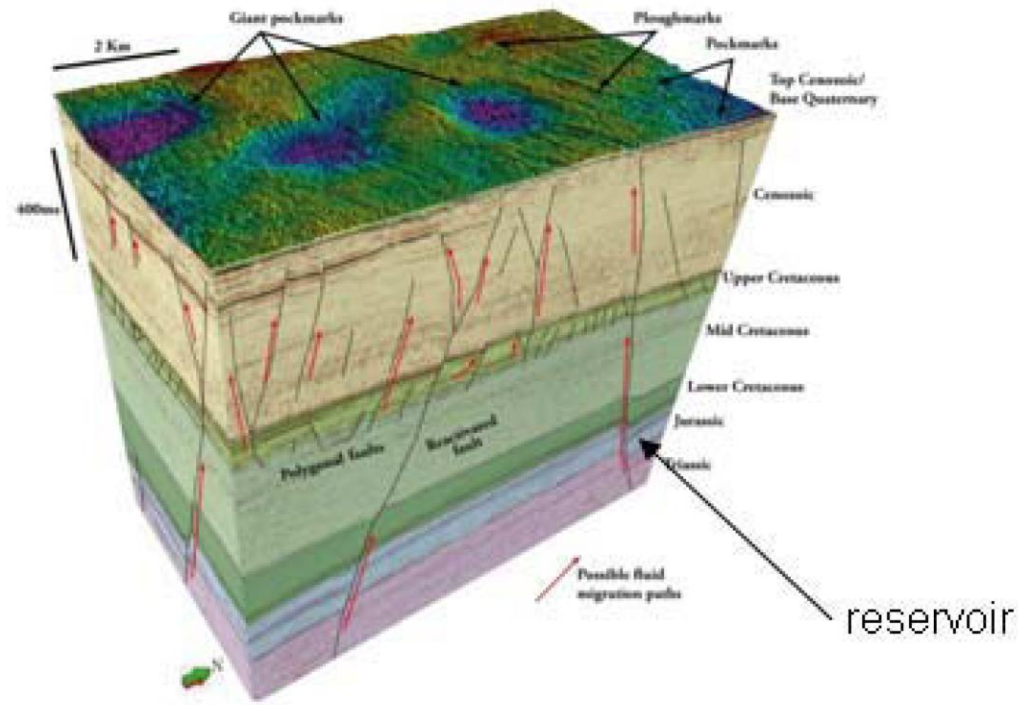

Figure 3. Large pockmarks (about 2 km diameter) identified at the top of the Cenozoic unconformity in the Hammerfest Basin (Barents Sea) (Ostanin et al., in preparation)