In Development

Australia & New Zealand Margins Initiative | Phase 2

Thermal Regimes of the Western Australian Transform Margins

Principal Investigator:

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Investment per Sponsor
$69k (USD)

Duration
12 months

Project I 01069_3

Value

- The identification of pull-apart regions whose source rocks reached an oil window without adequate burial, but with the help of thermal transients controlled by transform fault-associated factors.
- New thermal models to replace existing thermal models that were developed by tools originally designed for rifted margins.
- Identify the regions where the source rock kitchens may have reached the hydrocarbon expulsion stage under the burial that would not be sufficient in the case of rifted margins.

Key Deliverables

1. Map of continental crust thickness distribution,
2. Set of maps on stratigraphic gaps associated with erosional unconformities spanning from the mid-Jurassic to Turonian unconformities;
3. Set of maps on fault activity timing and type distribution;
4. Maps on magmatic rock lithology and emplacement timing distribution;
5. Map of pull-apart basin distribution;
6. Two 3-D finite-element models of thermal history in time for the Zeewyk-Houtman and Joey Wombat transform margins (see Fig. 1 for location); and
7. 1-D source rock maturation models made for several clusters of pseudo-wells targeting distinct pull-apart areas located in the regions of calculated 3D models.

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Objectives

To develop the large-scale thermal history models for the main West Australian transform margins in 3-D and time. Use developed thermal data as input for source rock maturation models along a set of pseudo-wells characterizing a number of pull-apart terrains at these margins and their immediate surrounding.

Value to Sponsors

To improve the understanding of the thermal regimes associated with transform margins that dominate the Western Australian continental margins (Figure 1). The understanding will arrive from the three-dimensional finite-element modeling done in time by a thermomechanical coupled simulation. The new thermal models will replace the existing thermal models that were developed by tools originally designed for rifted margins. Thus, the new modeling will replace the simple thermal models, which are characterized by rift and break-up related thermal peak and subsequent cooling, with realistic models that contain the effect of thermal transients developed along the transform fault systems during their oceanic/continental stage.

Calculated thermal histories will directly feed into source rock maturation models done by standard modeling programs along a series of pseudo-wells targeting both transform margin and pull-apart margin segments. What is especially attractive is the prospect of being able to identify the regions where the source rock kitchens may have reached the hydrocarbon expulsion under the burial that would not be sufficient in the case of rifted margins.

Major Goals

To develop:

1. Maps of erosional event timing and distribution;
2. Maps of fault type and activity timing;
3. Magmatic event timing and distribution;
4. 3-D models of thermal history with time for two main transform margins; and
5. 1-D models of source rock maturation history for a set of representative pseudo-wells, constrained by determined 3-D thermal models.

Rationale

A brainstorming session at the final meeting of the Sheared Margins of Western Australia project (Phase 1 of the Australia and New Zealand Initiative) that took place during 3-4 August, 2015, resulted in the understanding that Phase 1 has managed to deliver all necessary input data for the successful modeling of the thermal history at transform margins by finite-element techniques using the thermomechanical coupled simulation.

Existing thermal models have been developed using standard tools designed for rifted margins. On the contrary, planned finite-element models done using the Ansys program will manage to honor the effect of thermal transients caused by migrating zones of newly accreted oceanic crust together with sea floor-spreading ridges, laterally clearing transform margins during the ocean-continent stage of transform activity.

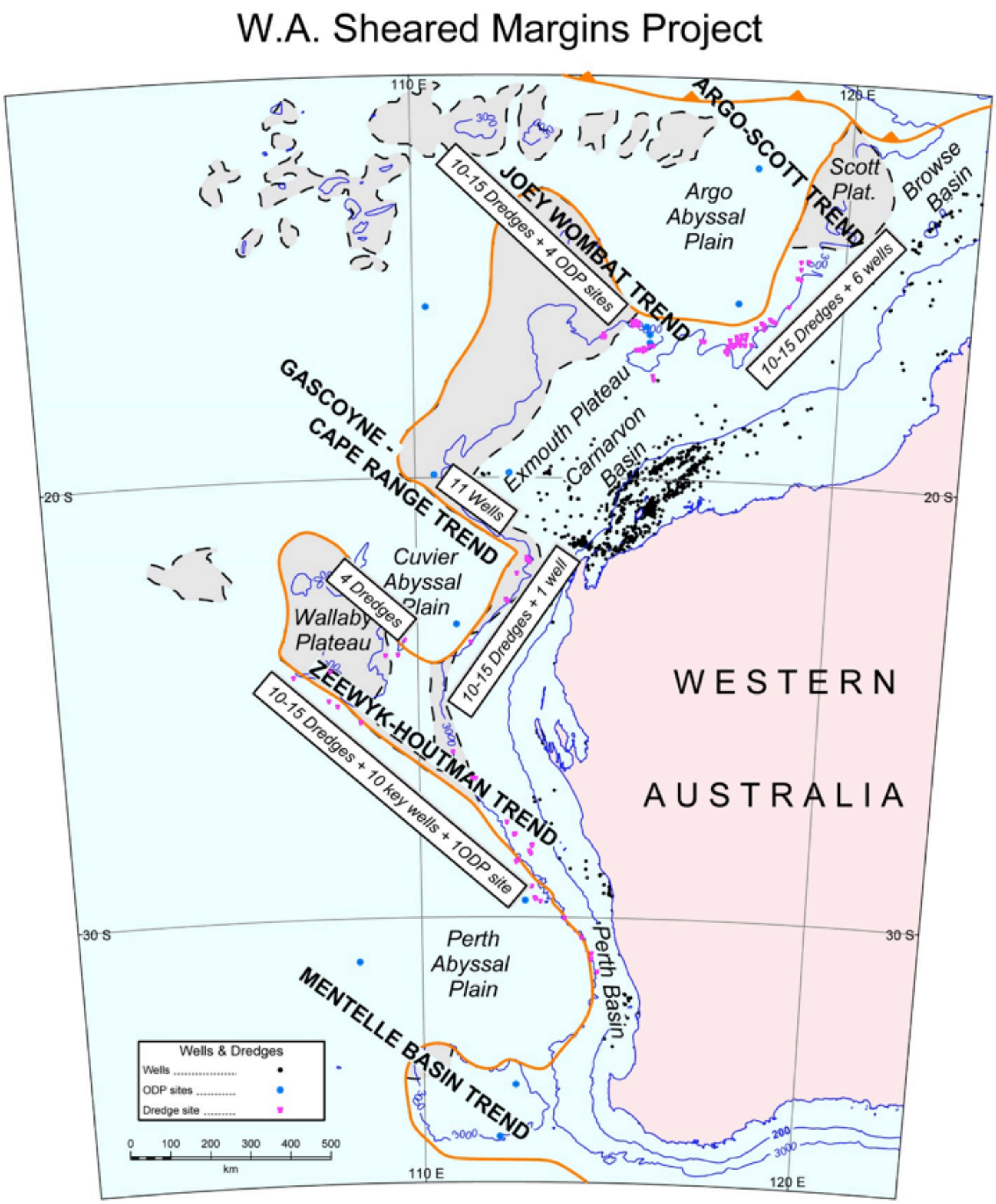

Figure 1.1 Figure 1. Individual structural provinces of the study area together with wells and dredges (dots) that were sampled and analyzed by the Phase 1 study.

The Phase 1 sponsors and research team share the opinion that thermal models specially designed for transform margins have a fair chance to identify specific pull-apart areas along these margins whose source rocks may have reached an oil window even without the amount of burial required at rifted margins, which is the main motivation for potential sponsors to join the Phase 2 study.

Both the sponsors and research team see a good potential for the Phase 2 study from the pull-apart basin and post-pull-apart passive margin analogues worldwide. For example, the Los Angeles Basin, California, provides an example of the World's richest petroliferous basin (Peters et al., 2014), containing five oil tribes and twelve families. Each of them migrates from a source rock deposited in a different local pull-apart of this pull-apart terrain that covers an area 70 by 30 km large. Each local pull-apart depression contains different source rock organofacies. The pull-aparts were developed in the releasing bend of the dextral continental transform fault system during the time span between base middle Miocene and base Pliocene (Ingersoll and Rumelhart, 1999). Here, marine source rocks fed the turbiditic reservoir rocks.

The Vienna Pull-apart Basin represents another example. It was formed between the early/middle Miocene boundary and base late Miocene at the releasing bend of the sinistral continental transform fault system. Apart from several syn-pull-apart source rock facies, such as the Karpathian Schlier, being 1 km thick at present and deposited in 1 million years, important source rocks also come from the pre-pull-apart section. Syn-pull-apart source rock facies vary from older marine to younger deltaic and lacustrine.

Yet another example comes from the Central Sumatra Basin. It is represented by at least five individual basins, most likely developed at both releasing bends and horse-tail structures of the dextral continental transform fault system. Individual pull-apart depressions provide source rocks that span in organic richness from several % TOC to 24% TOC (Williams and Eubank, 1995). They are either part of the lacustrine Pematang Brown Shale or the Coal Zone formations.

Because the pull-apart segments of transform margins have been explored using the tools developed for rifted margins, they are characterized by mixed success. However, there are several analogues that look rather promising. One of them is the releasing offset of dextral transform faults in the offshore Ivory Coast-Ghana, where the Jubilee discovery was made. It proves the petroleum system that contains both source and reservoir rocks deposited during the oceanic-continental stage of the transform development.

The second example is the sinistral transtensional transform fault system between the South Gabon Basin and Niger Delta, which contains numerous pull-apart terrains (Rosendahl et al., 2005). The discoveries made in some of them, e.g., the Douala and Rio Muni Basins, are particularly encouraging. Ceiba, Okume, Zingana and Alba discoveries prove the existence of petroleum systems, which are located in the passive transform margin development stage of the transform fault system.

A similar example comes from offshore Guyana, where the Liza discovery was made in the passive margin setting that evolved from the earlier sinistral horse-tail structure located at the eastern terminus of the large transform fault system.

All these examples needed extra burial for their source rock kitchens to reach the hydrocarbon generation. It was either transpression-related extra sediment transport onto pre-existing pull-apart basins (the Los Angeles Basin case), or extra sediment deposition due to a subsequent extensional event (Vienna Basin and Central Sumatra cases), or extra sediment deposition due to the development of a large prograding wedge younger than and unrelated to the transform fault system development (Ivory Coast-Ghana, Douala-Rio Muni and offshore Guyana cases).

Lacking such extra sediment deposition help, the successful pull-apart segments of the Western Australian margin would require help from thermal transients related to the lateral passage of new oceanic crust and spreading ridges. The search for such sweet spots is the primary goal of the Phase 2 study.

Project Strategy & Research Program

The Phase 2 strategy is to use the data set developed by the Phase 1 study, which:

1. determined the exact ocean-continent boundary;
2. developed detailed break-up propagation timing in the study area;
3. dated the associated post-breakup uplift;
4. interpreted fault kinematics and timing in seismic images;
5. mapped syn-breakup magmatic products; and
6. developed the first-generation crustal thickness map for the continental crust,

and develop the 3D finite-element models of the thermal history of main transform margins of Western Australia. Furthermore, the thermal histories read for specific pull-apart-characterizing clusters of pseudo-wells will provide an input for organic matter maturation history modeling.

The entire research project will conclude with the identification of pull-apart regions whose source rocks reached an oil window without adequate burial, but with the help of thermal transients controlled by transform fault-associated factors.

The research program will be split into two modules; tectonosedimentary and thermal ones. Each chapter of the Phase 2 report will include a short text. Model descriptions will be included.

Research Module 1 – Tectonics & Deposition

Rationale

Module 1 accumulates and synthesizes the last missing tectonic and depositional data prior to proceeding with Module 2 focused on a thermal history definition. The work begins with the gathering of key 15-20 depth-migrated seismic sections from Phase 2 sponsors. They are those crossing the ocean-continent boundary and selected from those successfully interpreted in time-migrated versions in the Phase 1 study. They will help to refine the crustal thickness map developed in the Phase 1 study. A set of maps on stratigraphic gaps associated with the middle Jurassic, late Jurassic, very early Cretaceous, Aptian/ Albian and Turonian erosional unconformities will be refined, using the data from all existing wells. Fault type and fault activity maps will be developed using all identified and determined faults from the seismic images – the work that was done in the Phase 1 study. Module one will end with analytical work focused on dating the syn-breakup, magmatic activity and resultant lithologies.

Anticipated Results

1. Map of continental crust thickness distribution
2. Set of maps on stratigraphic gaps associated with erosional unconformities spanning from the mid-Jurassic to Turonian unconformities;
3. Set of maps on fault activity timing and type distribution; and
4. Maps on magmatic rock lithology and emplacement timing distribution.

Research Module 2 – Thermal regimes

Rationale

Module 2 develops the thermal foundation for successful (and unsuccessful) petroleum systems. During its quick initial homework, it calculates tables of spreading rates per time intervals and spreading ridge migration rates along the Zeewyk-Houtman and Joey Wombat transforms (see Figure 1 for location) and identifies all areas with pull-apart basins along them.

Then it proceeds with 3D finite-element modeling of the thermal history in time for the two margin segments. Apart from full 3D thermal history results, it populates a set of pseudo-well clusters targeting several pull-apart areas with detailed thermal history data that serve as the input for 1D PetroMod modeling of their source rock maturation and expulsion histories.

It concludes with the identification of pull-apart areas that made it into the oil window with their source rock strata.

Anticipated Results

1. Distribution map of pull-apart basins along Zeewyk-Houtman, Cape Range and Joey Wombat transform margins;
2. Two 3D thermal history models with time for the Zeewyk-Houtman and Joey Wombat transform margins;
3. Set of 1D PetroMod models along pseudo-wells characterizing key pull-apart areas along the Zeewyk-Houtman and Joey Wombat transform margins; and
4. Location map of pull-apart source rock kitchens that may have reached an oil generation window.

Data Sources

Type of data	Quantity
2-D reflection seismic profiles and profiles through 3D seismic volumes for geoseismic trace sections or geological cross sections and regional geological cross sections Interpreted seismic data are in Petrel format	Portion of the 2 TB open-file data package interpreted in the Phase 1 study
well logs, well completion reports, destructive analyses, hydrocarbon field reports	A portion of the 2 TB data package, gathered and organized in the Phase 1 study. Database with organized data consists of data on lithologies, depositional environments, stratigraphy, reservoir porosity and permeability.
gravity data	A number of different gravity data sets, calculated in the Phase 1 study, including: Free-air data onshore and offshore, first vertical derivative of the Free-air data, total horizontal derivative of the Free-air data, dip azimuth of the Free-air data, dip-azimuth of first vertical derivative of the Free-air data, dip-azimuth of total horizontal derivative of the Free-air data, Bouguer data onshore and Free-air data offshore, Bouguer data onshore and offshore, Isostatic anomaly data onshore and offshore, several different bandpasses of the Isostatic anomaly data, first vertical derivative of the Isostatic anomaly data, total horizontal derivative of the Isostatic anomaly data, dip-azimuth of the Isostatic anomaly data.
magnetic data	A number of different magnetic data sets, calculated in the Phase 1 study, including: Total Magnetic Intensity data, total horizontal derivative of the Total Magnetic Intensity data, first vertical derivative of the Total Magnetic Intensity data, dip-azimuth of the Total Magnetic Intensity data.
topographic data	A number of different topographic data sets. All these data sets were merged and calculated from data sets from multiple sources during the Phase 1 study.
thermal data	The surface heat flow map from the International Heat Flow Commission covers the entire study area. Well-based thermal data gathered and organized into a comprehensive database during the Phase 1 study.
maps	Continental crustal thickness, oceanic/continental boundary, magmatic rock distribution, break-up timing and kinematic, and spreading ridge location in time maps
geochemical data	The geochemical database for the study area was made from literature and well reports on rocks and hydrocarbons. It was enhanced by original analyses of samples (see Figure 1 for location) taken in Geoscience Australia Canberra and Perth core repositories and the Kochi Deep Sea Drilling Project core repository, including organic matter maturity data, and (U-Th)/He and fission track analyzes made on sampled apatites. Furthermore, a set of samples of magmatic rocks was taken but not analyzed during the Phase 1 study from mentioned well and dredge depositories for the purpose of age dating to be performed in Phase 2.

Deliverables

The main focus of interpretation is to understand the thermal history of individual transform margins from the time of rifting initiation till the present, its difference from the thermal history of rifted margins and the role of various factors in its control. Each chapter of the report, focused on individual project tasks, will include a short text. Arc GIS format databases with full documentation will be enclosed.

Specific deliverables include:

1. Map of continental crust thickness distribution;
2. Set of maps on stratigraphic gaps associated with erosional unconformities spanning from the mid-Jurassic to Turonian unconformities;
3. Set of maps on fault activity timing and type distribution;
4. Maps on magmatic rock lithology and emplacement timing distribution;
5. Map of pull-apart basin distribution;
6. Two 3D finite-element models of thermal history in time for the Zeewyk-Houtman and Joey Wombat transform margins (see Figure 1 for location); and
7. 1D source rock maturation models made for several clusters of pseudo-wells targeting distinct pull-apart areas located in the regions of calculated 3D models.

Research Team

Staff	Expertise/Affiliation
Michal Nemčok, Ph.D.	Principal Investigator, Research Professor, Structural Geology
Júlia Kotulová, Ph.D.	Co-Principal Investigator, Thermal history modeling
John Conolly, Ph.D.	Petroleum Geology, EGI Australia
Prof. Andreas Henk	Structural Geology
Charles Stuart	Structural Geology
Samuel Rybár, Ph.D.	Structural Geology
Jana Rigová	Thermal history modeling
Silvia Králiková, Ph.D.	Thermal history modeling
Štefánia Sliacka	Research Assistant, Structure/GIS
Marína Gaži	Research Assistant, Structure/GIS
Paul Adams	GIS Specialist, EGI Australia

Project Timeline & Investment

Project sponsors and participants will be updated regularly regarding analyses, models and their interpretations. Three group meetings per phase (kick-off, mid-term and final meetings) will be held to assess the progress and provide guidance. Notice of the project kick-off meeting will be announced to all sponsors.

The project is planned for 1 year. Anticipated investment per sponsor is $69,000 (USD).

Tectonosedimentary Module (1)	■	■	■	■	■	■						
Thermal Module (2)	■	■	■	■	■	■	■	■	■	■	■	■
Month	1	2	3	4	5	6	7	8	9	10	11	12

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AT THE UNIVERSITY OF UTAH
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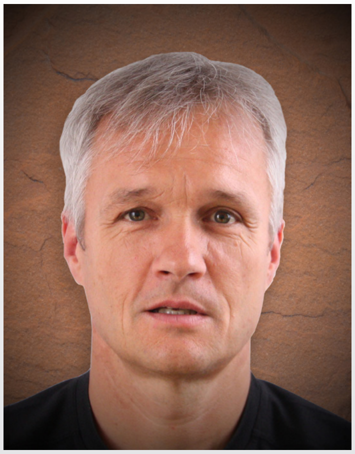

Michal Nemčok, PhD

Research Professor

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Research Interests

- Continental break-up processes and controlling factors
- Thrustbelt development and controlling factors
- Fracture development prediction

Michal holds a Ph.D. in Structural Geology from the Comenius University, Bratislava. He has 30 years of applied and basic research experience at the Slovak Geological Survey, University of South Carolina, University of Wales, Cardiff, Imperial College London, University of Salzburg, University of Wurzburg, and University of Utah. He joined EGI in 1998 and is a Research Professor and Structural Group leader. Michal has published 80+ articles, coauthored 5 monographs, and coedited five books.

Continental Break-up Processes & Controlling Factors

Continental break-up research focuses on both extensional and transform settings, with a focus on driving mechanisms and controlling factors to achieve predictive models with respect to structural architecture, thermal regimes, and petroleum systems. The main research contribution includes understanding anomalous thermal and uplift histories of transform margins, break-up mechanisms in extensional settings, and micro-continent-releasing mechanisms. A summary of his last eight years of break-up research is recorded in a monograph titled *"Rifts and Passive Margins; Structural Architecture, Thermal Regimes and Petroleum Systems"* published by Cambridge University Press, and authored by Nemčok, M., along with various research articles

Thrustbelt Development & Controlling Factors

Michal's current research focuses on the thrustbelt-foreland interactions, with a concentration on driving mechanisms and controlling factors behind thick-skin tectonics, foreland plate flexure mechanisms, and flexural faulting in control of structural architecture and play concept elements. The main research contribution includes the factors and mechanisms leading to the lack of foreland flexing and transitions from initial inversion to full accretion. Accompanying research focuses on modeling of the fluid flow mechanisms occurring in the thrustbelt front and its foreland. A summary of thrustbelt research is written in a monograph called *"Thrustbelts; Structural Architecture, Thermal Regimes and Petroleum Systems",* published by Cambridge University Press, and authored by Nemčok, M., Schamel, S. and Gayer, R.. Current research findings are summarized in several articles included in the Geological Society of London Special Publication 377, which is edited by Nemčok, M., Mora, A., and Cosgrove, J.

Fracture Development Prediction

Fracture prediction research includes both detailed well core, rock outcrop and numerical simulation studies focused on predicting timing, location and kinematics of developing fractures. Most of the fracture studies come from thrustbelts, although some core-based studies come from various geothermal reservoirs. The main research contribution includes tools capable of predicting fracture locations, kinematics and propagation timing in two and three-dimensions for hydrocarbon reservoirs in thrustbelts, which were tested by well-based fracture data. Accompanying research includes understanding the role of mechanical stratigraphy on developing structural architecture. This research is published in a number of journals run by structural and geothermal communities.

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Research Interests

- Unconventional Gas Systems
- Organic geochemistry
- Petroleum geology
- Organic petrology
- Basin modeling (PetroMod)
- Petroleum systems
- Anoxic events
- Calibration of organic and inorganic thermometers

Júlia Kotulová, PhD

Research Scientist

Júlia earned a Ph.D. in Geology, an RNDr. (M.Sc. equivalent) in Geology, and a B.Sc. in Geology and Geochemistry from Comenius University, Bratislava, Slovakia. She comes to EGI with extensive experience as a geochemist and petroleum geologist and spent the last nine years working at the Department of Geophysics and Non-Renewable Energy Sources, State Geological Institute of Dionýz Štúr (Geological Survey), Bratislava, Slovak Republic. Prior to this, Julia worked with the Geological Institute at Slovak Academy of Sciences. Julia collaborates with the geochemistry lab and other researchers in the Salt Lake City office from her primary location in EGI's Bratislava office.

Research Related to Hydrocarbon Systems

- Integration of geology, geochemistry, and basin modeling for a holistic understanding of hydrocarbon generation, migration, entrapment, and preservation in order to identify regional characteristics and to de-risk new exploratory plays and prospects. Design, acquisition, implementation and interpretation of geochemical data applied to petroleum exploration and exploitation.
- Design, implementation and management rock, oil, and gas sampling and analytical programs.
- Organic geochemistry research into the molecular and isotopic composition of source rocks, oils, and gases for reservoir geochemistry, source rock quality, and thermal maturity evaluation.
- Organic petrology research with an emphasis on source rock evaluation, coal and paleoenvironmental/organic facies characterization; multi-dimensional geochemical basin modeling for the reduction of petroleum exploration risk.

Global Basin Studies

Júlia has experience with various types of basins around the globe – from the Carpathian accretionary wedge, fore-arc basins, back-arc Black Sea and Danube Basins, and the intra-arc Transcarpathian Neogene Basin to the Intermountain Basins of Slovakia – with a focus on petroleum systems, geohistorical models, thermal evolution, and fluid flow dating and duration. Her experience with passive margin basins includes the Central and Equatorial Atlantic and NW African margins. She also has experience with shale gas research (GASH project) for biogenic and thermogenic shale gas systems, geological storage of CO_2 as related to the Northern promontories of the Pannonian basin system, Ocean Anoxic Events research (Aptian OAE 1a and Oligocene Antarctic glaciation Oceanic Anoxic Oi-1 events), PetroMod geochemical models and Petrel 3-D geological models (East Slovakian Neogene and Intermountain Horna Nitra Neogene basins), and visual kerogen analysis (Tethys: Aptian; Paratethys: Cretaceous to Neogene in the Carpathian accretionary wedge and the Circum Black Sea region, Neogene in the North part of the Pannonian Basin).

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Research Interests

- Global exploration in frontier basins
- Peer assists in basin analysis
- Risk analysis of petroleum systems
- Australian, P.N.G. & New Zealand geology

John Conolly, PhD

Affiliate Scientist

EGI Affiliate Scientist Dr. John Conolly was the key scientist who developed the seminal proposal to evaluate rift systems of North Africa that was funded by the National Science Foundation in 1972. He was instrumental in helping to establish EGI in its founding in 1972 as the Earth Science and Resources Institute (ESRI) at the University of South Carolina. Currently Managing Director of Petrofocus Consulting, John has 50 years experience in exploration of frontier basins worldwide.

John participated in the now famous Baltimore Canyon Trough Lease Sales and was a successful bidder for offshore acreage with Shell U.S.A., the major participant and operator. As a Principal of the frontier basin ventures, primarily as the 'innovator' and 'instigator' of these ventures, his work included all of the new joint ventures put together by the Sydney Oil Company during the period 1977 to 1988. These resulted in the participation in the discovery of fourteen new oil fields including the South Pepper, North Herald trend on the Northwest Shelf, and the Fairymount, Bodalla South, and Nockatunga trends in Queensland. Since 1988, he has worked as an independent consultant, creating new frontier plays and putting together new acreage blocks in the Northwest Shelf and other basins in Australia, Papua New Guinea, the Philippines, the S.W. Pacific Islands, and New Zealand.

John's work has spanned the globe and includes affiliations with such entities as the U.S. Naval Oceanographic Office, Scripps Institution of Oceanography, Lamont Doherty Geological Observatory at Columbia University, and numerous major partners in the energy industry and government agencies throughout Australia, New Zeland, South Pacific Islands, and the United States. He also founded Rawson Resources Ltd., an active oil explorer listed on the Australian Stock Exchange in 2005.

John has over 50 years of experience as a geologist and researcher in the energy and geosciences industry. He received a B.Sc. from the University of Sydney (1958) and his M.Sc. and Ph.D. from the University of New South Wales (1960, 1963). Between 1965 and 1971, he served as Professor of Geology at Louisiana State University, Columbia University, N.Y., and the University of South Carolina. John has been the recipient of numerous awards and honors spanning his distinguished career and is credited with over 100 articles in journals, conferences, and short courses. He was Keynote speaker to APG Conference India, in 2004 and 2006 and is an active member of the Petroleum Exploration Society of Australia and the American Association of Petroleum Geologists.

Dr. Conolly represents EGI in Austral-Asia and is actively involved with key research in sheared margins of Western Australia and in developing EGI's role in shale systems research across the Australian continent. He also conducts short course trainings and field courses for EGI Corporate Associate members.

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