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ENRECA Project

Enhanced research capacity to meet
future oil and gas challenges in Vietnam



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DESIGNED BY

Le Hong Van

MANAGEMENT

Vietnam Petroleum Institute

CONTACT ADDRESS

16th Floor, VPI Tower, Trung Kinh Street, Yen Hoa Ward, Cau Giay District, Ha Noi

Tel: (+84-04) 37727108 * Fax: (+84-04) 37727107 * Email: tapchidk@vpi.pvn.vn

Mobile: 0982288671

Cover photo: Interbedded sandstones and siltstones at outcrop on Bach Long Vi island. Photo: Hoang Anh Tuan

FOCUS

ENRECA Project
Enhanced research capacity to meet future oil and gas challenges in Vietnam

In 1995, the Geological Survey of Denmark and Greenland (GEUS) started a joint project with the Vietnam Petroleum Institute (VPI) to strengthen Vietnam's ability to assess its oil and gas resources. Training, research and technology transfer have been key-words in the close co-operation project, which has been funded through grants from the Danish Energy Research Programme (1997-1999) and since 2001 by DANIDA's ENRECA Programme. Training, research collaboration and technology transfer go hand-in-hand in the joint Danish and Vietnamese project which with success has enhanced the oil and gas expertise in Vietnam and laid out the track for future research collaboration.

"Demand-driven" research collaboration

The Vietnamese researchers were trained in oil-geological disciplines through teaching and participation in concrete research projects with the purpose of understanding the geological development and the potential for finding oil and gas in selected geological basins, thus addressing the needs of both the local energy authorities and the industry. As part of the research and capacity building activities the necessary technology was transferred to VPI and geological and geophysical databases were established to store the research results.

The fruitful research co-operation between GEUS and VPI was initiated in 1995 by carrying out joint research studies in northern Song Hong Basin. Following the successful completion of this 2-phase project in 2005, the ENRECA-3 phase project (Fig.1) was initiated in early 2007.

During the first phase of the ENRECA Project the research work focused on the analysis of the Phu Khanh basin. This work included a 400m deep core drilling operation on land - the ENRECA-1 well, contributing valuable information about the geology of both the onshore and offshore areas (Fig.2).

During the second phase, the research activities took place in the Malay-Thu Chu basin. This included drilling of a 500m deep ENRECA-2 borehole on the island of Phu Quoc (Fig.3) also contributing valuable information about the geology and the oil and gas potential of the area.

And finally, during the third and last phase of the project the geological research and assessment of the oil and gas potential were concentrated in the Song Hong basin, which included drilling of the 500m deep ENRECA-3



Fig.1 Location map of the ENRECA-1, -2 & -3 wells. The map shows the location of the ENRECA-3 well in the Song Hong basin, with a scale bar indicating 0 to 100 km. The map also shows the location of the ENRECA-1 and ENRECA-2 wells in the Malay-Thu Chu basin and the ENRECA-2 well in the Phu Quoc island.

Dissemination has been a key objective in the ENRECA project and through the years results of the research work have been presented to researchers and public stakeholders as well as representatives of the oil industry

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PETROVIETNAM'S OIL AND GAS PRODUCTION IN 2014 estimated at over 27 million tons

In the first 9 months of 2014, the Vietnam National Oil and Gas Group (Petrovietnam) produced a total of 20.34 million tons of oil equivalent (12.71 million tons of crude oil and 7.64 million m³ of gas). Petrovietnam will continue to strictly control the progress of exploration, field development and production projects both at home and abroad in order to ensure the fulfillment of plans to increase oil and gas reserves and production in 2014. It is estimated that for the whole year of 2014, Petrovietnam will produce over 27 million tons of oil equivalent.



Petrovietnam Chairman Nguyen Baun San and Vice President Le Minh Hong chaired the press conference. Photo: PTV

At the press conference held on 8 October 2014, Petrovietnam's Vice President Le Minh Hong informed that the Group has kept up a good pace of development and over fulfilled all its goals for the first 9 months of 2014. Oil and gas reserves have increased to 28.53 million tons of oil equivalent, or 81.5% of the yearly plan. Total oil and gas production reached 20.34 million tons of oil equivalent, which is equal to 108.7% of the 9-month plan and 79% of the yearly plan, representing an increase of 2.7% over the same period of 2013. Of this figure, crude oil accounted for 12.71 million tons, and gas 7.64 billion m³. Besides, Petrovietnam has produced and contributed 11.92 billion kWh of electricity to the national grid, and produced 1.23 million tons of urea fertiliser, 29.5 thousand tons of fibre and 4.06 million tons of various petroleum products. By the end of September 2014, Petrovietnam has earned a total revenue of VND 560.1 trillion and contributed to the State Budget VND 125.1 trillion. The value of Petrovietnam's contribution to the State Budget exceeds its 9-month target by 24% (equivalent to VND 24.3 trillion (~USD 1.14 billion)), which is very important in the context where collection of State Budget revenues continues to meet with numerous difficulties.

Works of equalisation, divestment, and corporate restructuring have been stringently and effectively carried out by Petrovietnam in accordance with the restructuring plan approved by the Prime Minister. Thrift practice and waste control are seriously deployed across the Group. All member units have implemented the Programme of Action for expenditure reduction and lower production costs. As a result, in 9 months of 2014, the Group has cut costs by VND 1.980 billion VND, equal to 58% of the yearly plan.

In the coming period, Petrovietnam will focus on completing the Strategy for development until 2025 and orientations towards 2035. At the same time, Petrovietnam will continue to seriously implement the Petrovietnam restructuring plan for the 2012 - 2015 period already approved by the Prime Minister as well as urge its member units to do so. In particular, the key tasks will be equalisation, divestment, enhanced competitiveness and operational efficiency. Petrovietnam will continue to strictly control the progress of exploration, field development and production projects both at home and abroad, ensuring the fulfillment of plans to increase oil and gas reserves and production in 2014. Besides, it will ensure the safe operation of Dung Quat Refinery, gas transportation systems, power plants, and fertiliser plants; ensure the implementation progress

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ENRECA Project

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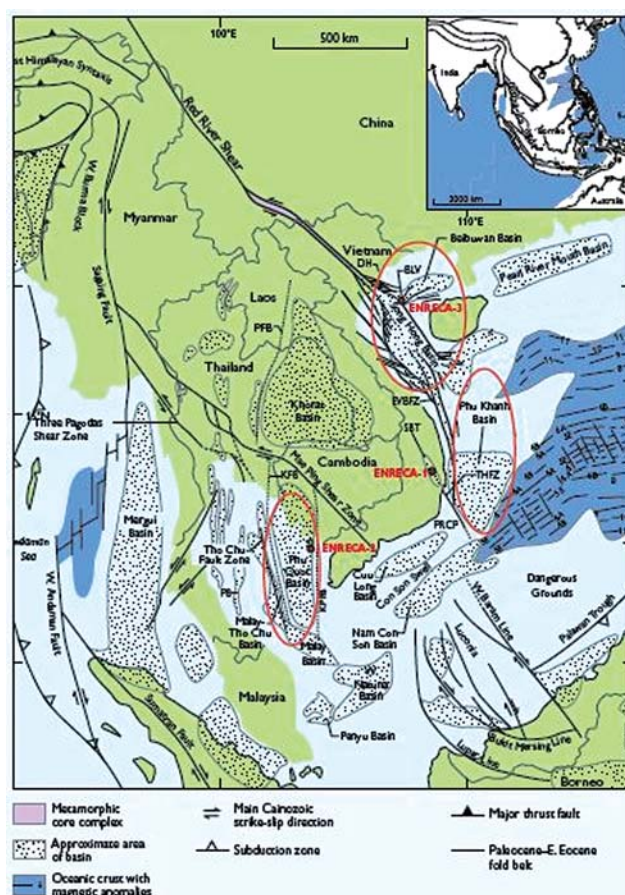


Fig.1. Location Map of the ENRECA-1, -2 & -3 Wells

core well at Bach Long Vi island (Fig.4) - a location of large interest for both researchers and oil companies operating in the region.

Dissemination has been a key objective in the ENRECA project and through the years results of the research work have been presented to researchers and public stakeholders as well as representatives of the oil industry



Fig.2. ENRECA-1 Well, Song Ba Trough, Middle Vietnam



Fig.3. ENRECA-2 Well, Phu Quoc island, South-western Vietnam



Fig.4. ENRECA-3 Well, Bach Long Vi island, North-eastern Vietnam

who are active in Vietnam. Furthermore, Vietnamese and Danish researchers have presented the results of their research collaboration at several international conferences, and joint Vietnamese-Danish articles have been published in local and international scientific journals.



Dr. Phan Ngoc Trung
General Director of VPI
ROLE OF ENRECA
PROJECT IN ENHANCING
RESEARCH CAPABILITIES
OF VPI

"The ENRECA Project has provided the framework for the long-term research co-operation between the Vietnamese and Danish geoscientists. Over the years VPI has certainly benefited a lot from the project's capacity building programme both by enhancing the geoscientific level of my institute's researchers with several MSc. and PhD. degrees but also by providing to us state-of-the-art technology, so my staff could practice their enhanced capabilities."

The Project has been implemented in a multi-cultural environment and that has been quite challenging and interesting from the Management point of view. Mutual understanding and respect have made us all stronger both at the involved researchers' and management's level in Vietnam and in Denmark.

I really believe that this achievement of strengthening the Human Capacity is at least equally important as the excellent research results that our researchers have jointly achieved, because this will contribute to the sustainability of the achieved results in the future.

Comparing to the starting point, that is almost twenty years ago, it is easy to confirm that our geoscientific research co-operation with our Danish colleagues has contributed greatly to enhancing the capabilities of both the VPI's researchers and the institute as a whole to better assess Vietnam's oil and gas potential."



Fig.5. Meeting of the ENRECA Project Management Team in Copenhagen, Denmark



Dr. Johnny Fredericia
GEUS General Director
IMPORTANCE OF
FUTURE RESEARCH
COLLABORATION
BETWEEN VPI AND
GEUS

"Looking from the Danish side, it is clearly evident that this long-term - Twinning-research co-operation between GEUS and VPI and our collabora-

tion with the universities in Denmark and Vietnam have been quite a learning experience both for us at Management level and for the involved researchers in my institute.

This that impresses me most, however, is the very fruitful and constructive co-operation between our scientists over the years that has resulted in excellent research results.

The dissemination and publication of these results, for sure, has enhanced and promoted the profiles of GEUS and VPI at national and international level.

But the research work and the need for new knowledge do not stop at the end of the ENRECA Project, therefore, we, here at GEUS, are looking forward to continuing our collaboration with VPI in the years to come, starting with the signing of the MOU in November 2014.

Joining the research forces of GEUS and VPI will not only make our research teams stronger but it will also provide the best possible sustainability of the achieved results on which we can jointly continue to build further on".

Sustainable capacity building

During the first phase GEUS geoscientists held courses in Vietnam, and Vietnamese researchers participated in on-the-job training programmes in Denmark and in Vietnam (Fig.6 & 7). Furthermore, collaboration was established between Vietnamese students from VPI and Hanoi University of Mining and Geology (HUMG) and junior researchers from the University of Copenhagen. A total of eight Vietnamese students completed their MSc studies during the first phase.

The training activities were expanded and during the second phase, the project not only aimed at capacity-building at VPI, but has also improved co-operation with universities in Vietnam and Denmark. With participation from teaching resources from the Department of Geosciences and Natural Resource Management (IGN) at the University of Copenhagen, joint MSc/PhD programmes were completed for nine younger researchers and students from VPI, HUMG and Hanoi University of Science (HUS). The programmes have also included introducing Vietnamese lecturers to modern teaching techniques such as those used at IGN.

During the project several geological expeditions were conducted among which the first ever joint geological expedition across northern Vietnam, where Vietnamese and Danish PhD. students and their tutors carried out geological surveys contributing substantially to the understanding of the geology in the region (Fig.8).

During the third and final phase of the project eight students have completed their MSc/PhD studies. Help to self-help has been the key word in this phase. Vietnamese PhDs educated through the previous phase of the project were used as



Fig.6. ENRECA Project, On-the-Job Training of VPI researchers, Hanoi



Fig.7. ENRECA Project, MSc. & PhD. candidates on fieldwork in Denmark



Fig.8. Vietnamese and Danish PhD. candidates and their tutors on joint fieldtrip, Northern Vietnam



Assoc. Prof. Dr. Le Hai An

Rector of HUMG

ROLE OF ENRECA PROJECT
IN EDUCATING OIL AND GAS
CANDIDATES AND COLLABORATION
OF HUMG AND HUS WITH
UNIVERSITIES IN DENMARK

"The ENRECA Project and through this the collaboration of HUMG and HUS with universities in Denmark and in particular our co-operation with ING at the University of Copenhagen have helped us greatly in our endeavours to improve the quality of MSc. & PhD. studies in our universities.

Joint lecturing in Copenhagen and Hanoi, studies and on-the-job training of our candidates locally and in Denmark, joint fieldtrips and close collaboration between Vietnamese and Danish lecturers have contributed to enhancing the curricula of the MSc. & PhD. studies both at HUMG and at HUS.

Our universities have also benefited from the technology transfer that has been provided by the ENRECA Project during Phases I, II & III. Access to state-of-the-art technical facilities is not always easy but through the project the access to appropriate technology has helped us to enhance our teaching and hands-on procedures to the benefit of not only the involved MSc. & PhD. candidates but also the junior students in general.

In my discussions with Dr. Nguyen Van Vuong, Dean of Faculty of Geology at HUS, and other colleagues in our universities we all agree that the ENRECA Project have brought the educational system in Vietnam closer to the needs and requirements of today's Oil & Gas industry, thus helping us to design tailor-made studies for our students to meet the future needs in both the public and private sectors".

supervisors for young students and MSc/PhD candidates to strengthen the sustainability of the achieved results.

From training to collaboration

The presented experiences, geo-scientific findings and capacity building achievements are part of the results obtained to date through the research co-operation between Danish and Vietnamese researchers and the implementation of the ENRECA Research Capacity Building project titled: Integrated Analysis and Modelling of Geological Basins in Vietnam and an Assessment of their Hydrocarbon Potential, grants from the Danish Energy Research Programme (EFP-1995) and since 2001 by DANIDA's ENRECA Programme.

The ENRECA Research Group within the co-operating institutes and universities has received valuable administrative and geoscientific support from a large



Dr. Nguyen Hong Minh

Deputy General Director of VPI

POSSIBILITY TO RECRUIT QUALIFIED VIETNAMESE RESEARCHERS AFTER THE PROJECT

"After my return from my advanced studies abroad back to VPI, I was privileged to be involved in the research co-operation between VPI and GEUS and I participated in several training activities of the project.

This gave me the opportunity of following the evolution of the project from very close and I got exposed to the challenging procedures for both carrying out high quality and integrated research work and training activities and in managing such a multi-disciplinary project.

Based on these personal experiences, I feel confident in saying that the ENRECA Project helped the involved MSc. & PhD. candidates from VPI, HUMG and HUS in enhancing their research capabilities, thus they can better meet the requirements of their demanding jobs after their studies, either these are in the public or in the private sector. Here I can add that we have several examples where Vietnamese scientists involved in the ENRECA Project have been advancing in higher positions within the public domain (i.e. VPI's EPC and Petrovietnam) or have been attracted by interesting jobs in the Oil & Gas industry operating in Vietnam and internationally.

At a personal level, I can say that my involvement in the project has helped me to improve my managerial skills and equipped me with experiences that now I can use for managing VPI's newly established Centre for Petroleum Training and Information (CPTI) where VPI can provide tailor-made training both internally in VPI and Petrovietnam and to external customers from the industry.

All these prove nicely that the ENRECA Project has enhanced our abilities in providing training of higher standards that makes it possible for the public and private sectors to recruit qualified Vietnamese researchers."



Mr. Phung Sy Tai

Former Deputy General

Director of Vietgazprom

INVALUABLE INPUT

TO SCOUTING

CAMPAIGNS

"I have followed the ENRECA research project since its early days

during my work at VPI and I have always been impressed about the quality of the joint research studies the Vietnamese and Danish scientists were carrying out.

After I moved to the oil and gas industry, I realised the great importance that these geoscientific results had and still have, not only for the Vietnamese Energy Authorities, but also for the industry that is active in Vietnam or they may consider doing so.

The publication of the new knowledge that the project has generated about the hydrocarbon potential of the Vietnamese margin has several times been an invaluable input to our scouting campaigns seeking for new opportunities to invest in the expansion of our exploration and production operations in Vietnam.

At the same time, this has been an excellent exhibition window for the enhanced capabilities of the researchers at VPI, making us at the industry to feel more confident on the reliability of their demand-driven research results that they may have carried out for us on a consultancy basis."

number of individuals at CCOP, Petrovietnam, VPI, HUMG, ING, GEUS, the Royal Danish Embassies in Hanoi and Bangkok, the Danish Energy Agency, DANIDA's Fellowship Centre (DFC) and DANIDA's Council for Development Research (FFU)... The project activities have strengthened the Vietnamese oil and gas research, and the project has gradually changed from more training oriented activities in the early phases to more research collaboration between the partners in the late phase. The project achievements have contributed to a transition from aid to trade oriented activities.

During the conclusion of the ENRECA project in November 2014, VPI's and GEUS' Management will sign a Memorandum of Understanding (MOU) for research collaboration, to jointly address

the future oil and gas challenges in Vietnam.

Dr. Phan Ngoc Trung, General Director of VPI, emphasised "Today's studies are certainly not a one-man show but they need a multi-disciplinary and integrated approach for fulfilling the requirements of the users. Therefore we are welcoming the continuation of this successful co-operation between our institutes VPI and GEUS, as this will also help VPI to be even better in meeting the future oil and gas challenges in Vietnam".

I. Abatzis



ASSESSMENT OF HYDROCARBON POTENTIAL OF VIETNAM'S TERRITORIAL WATERS AND CONTINENTAL SHELF

The "Assessment of hydrocarbon potential of Vietnam's territorial waters and continental shelf" project presided over and conducted by the Vietnam Petroleum Institute has been assessed as one of the projects which have made new and valuable contributions to petroleum geology. For the first time, the boundary between the Cenozoic sedimentary basins is determined on the basis of handling and interpreting a large volume of documents and geological-geophysical survey data, with sufficient scientific arguments and reliability necessary to guide oil and gas exploration activities, contributing to asserting and defending the national sovereignty.



Dr. Nguyen Quoc Thap - Vice President of Petrovietnam reported to Deputy Prime Minister Hoang Trung Hai on main results of the "Assessment of hydrocarbon potential of Vietnam's territorial waters and continental shelf". Photo: Ngoc Linh

The "Assessment of hydrocarbon potential of Vietnam's territorial waters and continental shelf" project presided over and implemented by the Vietnam Petroleum Institute is a project under the Master Plan for "Basic survey and integrated management of marine resources until 2010 and vision to 2020" (Decision No. 47/2006/QĐ-TTg). On that basis, the Vietnam Petroleum Institute has conducted 7 sub-topics on "Assessment of hydrocarbon potential and reserves" of 8 sedimentary basins (Song Hong, Phu Khanh, Cuu Long, Nam Con Son, Malay - Tho Chu - Phu Quoc, and Truong Sa - Tu Chinh - Vung May) and a general topic on "Overall assessment of hydrocarbon potential of the entire continental shelf and orientation for oil and gas exploration and production".

For the first time, the boundary between the Cenozoic sedimentary basins is determined on the basis of handling and interpreting a large volume of documents and geological - geophysical survey data, with sufficient scientific arguments and reliability necessary to guide the exploration of oil and gas resources in particular and minerals in general.

Some basic issues of the East Sea tectonics such as faulting activity of the major systems: Song Lo, Vinh Ninh, Song Chay, Song Hong, Rao Nay, West Tri Ton, Tam Ky - Phuoc Son, Cu Lao Xanh, East Vietnam Slope, Tuy Hoa shear zone, Su Tu Den - Phu Quy, Bach Ho - Rang Dong, Mae Ping - Song Hau, Song Dong Nai, Hong - Mang Cau, Da Chu Thap - Da Tay, Vung May, West Truong Sa, and Ba Chua - Kim Long; forming mechanisms and geological history of tectonic units in pre-rift, rift and post-rift stages; magmatic eruption in different periods; as well as sedimentary conditions and environment have been elucidated, compared, contrasted, and linked among regions generally, unanimously and systematically.

The geological structure of sedimentary basins, zones and regions, composition and trap are made precise with new data and application of modern technology and software, ensuring adequate reliability for research on zoning and assessment of oil and gas potential. The structure units of grade I and II in the sedimentary basins have been established and standardised.

In the project, one set of maps scaled 1:1,000,000 has been made for the entire continental shelf and waters of

Vietnam, including: 5 structure maps, 4 isopach maps, 2 source rock and maturity maps, 1 tectonic zoning map, 1 map for structures and potential, 4 maps for structures collection, and 1 map for oil and gas prospect zoning. These are the first maps built comprehensively, adequately and rather completely on the basis of combining equivalent maps in greater scale (1:200,000 - 1:500,000) of sedimentary basins, meeting the requirement of planning and management of marine environment and resources in the coming years and in the long term.

The results of analysing and evaluating petroleum system: source rock, containing rock, cap rock, traps and hydrocarbon migration time of each zone, region, area and sedimentary basin are used as bases to determine the range and classification of prospects including pre-Cenozoic fractured basement, Oligocene sandstones, Miocene sandstones, and Miocene carbonate, as well as to establish the areas of high potential (areas prone to oil potentials, areas prone to gas potentials), areas of average potentials, low potentials and areas with unclear potentials.

The research results are the bases for the Vietnam Petroleum Institute's proposal of specific orientation for the oil and gas exploration in the future, with priority given to the areas of much hydrocarbon potential in sedimentary basins on the sea and continental shelf of Vietnam. For sedimentary basins/new regions where exploration activities are carried out but no field/object is put into oil and gas production, it is necessary to concentrate on research, additional 2D and 3D seismic acquisition, and selection of potential objects for exploration drilling in order to increase the reserves of all levels. For traditional basins/areas, it is necessary to promote research of potential accuracy, additional exploration drilling and appraisal of specific areas/objects so as to increase the proved reserves and production.

For scientific and technological research, it is important to strengthen basic research and investigation; explore and apply modern methods and technologies to study the fractured structure and trap distribution size and reevaluate oil and gas reserves of the basement rocks of Cuu Long, Nam Con Son and Northeastern Song Hong basins; carry out quantitative analysis and evaluation of oil and gas prospects of non-structural and mixed traps in Cuu Long and Malay - Tho Chu basins, and selection of drilling well location; study and evaluate gas accumulation in the upper Miocene, Pliocene, and Pleistocene sediments in Song Hong and Phu Khanh

The "Assessment of hydrocarbon potential of Vietnam's territorial waters and continental shelf" project has built thousands of diagrams, maps, charts, sections, and figures to show the detailed geological structure and the oil and gas potential of 8 sedimentary basins and the entire continental shelf of Vietnam. In particular, the project has built the map of tectonic elements for each sedimentary basin; maps of magnetic anomalies and gravity anomalies for the study areas; structural maps for (isochrones/depth) thickness of the layers/objects with petroleum potential; ancient maps of facies and sedimentary environments; maps of source rock, maturity and petroleum migration; maps of the fields, prospects and oil and gas plays; and maps of prospect zoning/risk assessment for layers/objects containing oil and gas.

basins; concurrently study and reevaluate the hydrocarbon potential in Miocene age carbonate trap in the Southern part of Song Hong and Nam Con Son basins; study and evaluate non-conventional traps (fractured tight clay, gas-containing coal layer, and gas hydrate accumulation, v.v.); and study the rule of distribution and CO₂ concentration in the oil and gas fields, as well as mining technological solutions.

According to Dr. Phan Ngoc Trung, General Director of the Vietnam Petroleum Institute and Project Manager, the project assessed oil and gas potential under 4 levels: sedimentary basins, petroleum system, play, and prospects. From the basic surveys and studies conducted, the Vietnam Petroleum Institute has developed a reliable and constantly-updated scientific database of hydrocarbon potential and reserves in the territorial waters and the continental shelf of Vietnam. The project has provided data to facilitate the formulation of policies and development of strategies for oil and gas prospecting, exploration and production; and proposed measures for the State to manage and rationally exploit the marine resources and environment in a scientific, effective and efficient manner, satisfying the requirements for sustainable economic development and contributing to safeguarding the national sovereignty and security. This is also an opportunity for the oil and gas industry of Vietnam to develop and apply modern technologies, train high quality management/research staff in the field of marine mineral exploration and management.

Nguyen Thanh

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Petrovietnam Chairman Nguyen Xuan Son and Vice President Le Minh Hong chaired the press conference. Photo: PVN

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Su Tu Nau field. Photo: PVEP

No.	Content	Unit	Goal set by Government 2014	Goal for 4 th quarter of 2014
1	Oil and gas production	Million tons of oil equivalent	25.71	7.67
	Oil	Million tons	16.21	4.91
	- Vietnam	Million tons	14.37	4.44
	- Abroad	Million tons	1.84	0.47
	Gas	Billion m ³	9.50	2.76
2	Electricity	Billion kWh	15.70	4.80
3	Urea	Million tons	1.525	0.394
4	Petroleum products	Million tons	4.636	1.352
5	Total revenue	Trillion VND	666.5	202.0
6	Contribution to State budget	Trillion VND	140.5	41.2

of its projects; and focus on developing the market for the new products (fibre and biofuel).

At the press conference, Petrovietnam's leaders answered many questions from the journalists concerning important issues such as the implementation

of Petrovietnam Restructuring Plan, the progress of equitisation and divestment from non-core businesses; Petrovietnam's investment in foreign countries; the progress of implementation of major oil and gas projects: Ca Voi Xanh, Junin 2, Block B, Long Phu 1 Thermal Power Plant, expansion and upgrading of Dung Quat Refinery; electricity prices and the Group's participation in the competitive electricity market; roadmap for trading E5...

Under the yearly plan set by the Government for 2014, Petrovietnam will produce 25.71 million tons of oil equivalent (16.21 million tons of crude oil and 9.5 billion m³ of gas); produce 15.7 billion kWh of electricity, 1.525 million tons of urea, and 4.636 million tons of petroleum products. Petrovietnam's Chairman Nguyen Xuan Son emphasised the determination to focus all resources to complete ahead of schedule the key tasks in 2014, thus actively contributing to the cause of construction and development of the country and the assurance of the national energy security, at the same time enhancing credibility and promoting the brand name of Petrovietnam in the domestic and international markets. With the greatest effort and determination, Petrovietnam is striving to complete its tasks early, over-fulfil all its production and business goals for 2014, and create a strong momentum for development in the next period.

Hong Minh

ADVANCED ANALYSIS OF BASINS ALONG THE VIETNAMESE MARGIN AND THE GREATER REGION: CENTRAL VIETNAM'S NEOGENE CARBONATE PLATFORM DEVELOPMENT

Michael B.W.Fyhn¹, Henrik I.Petersen², Lars H.Nielsen¹, Hoang Anh Tuan³, Nguyen Trung Quan³
Tran Chau Giang⁴, Nguyen Dinh Nguyen⁵, Nguyen Thi Minh Hong⁶, Ioannis Abatzis¹

¹Geological Survey of Denmark and Greenland (GEUS)

²Former GEUS, now Mærsk Oil & Gas

³Vietnam Petroleum Institute

⁴Petrovietnam Exploration Production Corporation (PVEP)

⁵Hanoi University of Science (HUS)

⁶Hanoi University of Mining & Geology (HUMG)

Email: mbwf@geus.dk

Summary

For close to 20 years, Vietnamese geology and hydrocarbon prospectivity have been studied by the ENRECA research team (VPI/Petrovietnam & GEUS). During the course of this study, on- and offshore basins from the Hanoi Trough in the north to the Malay-Tho Chu basin in the south have been analysed. The research carried out includes amongst others tectonic, depositional, petrographic, geochemical, provenance and uplift analysis. In this paper, the ENRECA-work is exemplified by a study of Neogene carbonate growth along the central Vietnamese margin.

Miocene carbonate platforms cover a large part of the Central Vietnam's East Vietnam Sea margin. Early carbonate deposition took place on two regional platforms separated by a narrow depression developed along the trace of the East Vietnam Boundary Fault Zone. West of the East Vietnam Boundary Fault Zone, the Tuy Hoa Carbonate Platform fringes the continental margin between Da Nang and Nha Trang. Here, platform growth initiated during the Early Miocene and continued until Middle Miocene time when regional uplift led to subaerial exposure, termination of platform growth and karstification. East of the fault zone, the Tri Ton Carbonate Platform was also initiated during the Early Miocene. Carbonate growth thrived during Early and part of Middle Miocene time and a thick, clean Lower and Middle Miocene carbonate succession covers the Tri Ton Horst and the Quy Nhon ridge. During the Middle Miocene, partial drowning resulted in the split-up of the Tri Ton Carbonate Platform. Repeated partial drowning events throughout the Middle and Late Miocene resulted in westwards retreat of platform growth and eventual platform drowning and termination of carbonate deposition. Modern carbonate growth continues on isolated platforms hosting the Paracel Islands farther seawards. The onset of widespread carbonate deposition largely reflects the Early Miocene transgression of the area linked with early post-rift subsidence and the opening of the East Vietnam Sea. The mid-Neogene shift in carbonate deposition is interpreted as a consequence of regional uplift and denudation of central and south Indochina starting during Middle Miocene time when the Tuy Hoa Carbonate Platform became subaerially exposed. Stressed carbonate growth conditions on the Tri Ton Carbonate Platform probably resulted from increased inorganic nutrient input derived from the uplifted mainland, possibly enhanced by deteriorated climatic conditions and rapid sea-level fluctuations promoting platform drowning.

Key words: Basin analysis, Neogene, carbonates, ENRECA project.

1. Introduction

The Vietnamese shores outline the western margin of the East Vietnam Sea that opened by oceanic spreading during Oligocene and Miocene time [2, 3, 8]. The Vietnamese margin is now largely passive, underlain by a major Cenozoic rift system. The rift basins fringe the margin for approximately 2,000km, but none the less, share a comparable evolution history. From North to South rifting commenced sometimes during the Eocene or earliest Oligocene and lasted till near the end of Oligocene time. The subsequent history is signified by thermal contraction with rifting and inversion taking place in some basins throughout the Miocene. Neogene

deposition is characterised by the vast amounts of siliciclastic sediments deposited mainly in deltaic to deep-marine settings along the margin of the East Vietnam Sea. In addition, carbonate platforms developed throughout the period and serve as excellent records of the geological development of the margin, its upland and the prevailing oceanographic conditions through time.

The Danish-Vietnamese collaboration research project, the ENRECA project (Enhancement of Research Capacities in developing countries) and its predecessor, has worked to improve the understanding of the Vietnamese geology and petroleum potential for almost 20 years. The ENRECA project initiated in 2001 with the aim of training Vietnamese geoscientists and conducting

demand-driven geological and exploration research. However, the Danish-Vietnamese geoscientific research collaboration dates back to 1995 when the Geological Survey of Denmark and Greenland (GEUS) and the Vietnam Petroleum Institute (VPI) started working together on assessing the petroleum potential of the Song Hong basin [1, 49, 51, 53, 55]. Since 2001, the ENRECA group has evaluated the geology and petroleum potential of the Phu Khanh [5, 21, 22, 23] Kua Luc [50], Nam Con Son [6, 21], Cuu Long [6, 21], Malay - Tho Chu [24, 52, 54] and the Phu Quoc [25] basins and in its latest phase is revisiting the Song Hong basin [26, 27, 56].

The ENRECA group has expanded during the years and apart from GEUS (Geological Survey of Denmark and Greenland) and VPI (Vietnam Petroleum Institute) presently encompasses the Institute of Geography and Geology from the University of Copenhagen, Petrovietnam, the Institute of Marine Geology and Geophysics, the Hanoi University of Mining and Geology, and the Hanoi University of Science. The ENRECA group further collaborates with international oil companies and a number of institutions in Vietnam and its neighbouring countries.

The research has been conducted by integrating information from seismic analysis with stratigraphic core well drilling, exploration well data, outcrop analogues, source rock and oil geochemical analysis, maturity modelling as well as petrographic, biostratigraphic, uplift and provenance studies [21, 24, 49, 50, 52, 54, 56].

Carbonate deposition and platform development from along the Song Hong, the Phu Khanh and the Nam Con Son basins have been studied during the course of the ENRECA Project [21, 22, 23, 26]. Cenozoic carbonates constitute one of the primary targets for petroleum exploration within the East Vietnam Sea region [13, 20, 35, 73, 76] (Fig.1). This is also true for the Vietnamese margin where considerable petroleum reserves are found and produced from Miocene carbonates in the Nam Con Son basin [43]. Miocene carbonates have been documented north of the Nam Con Son basin along the Vietnamese margin [21, 22, 23, 26, 34, 39, 59]. Although little explored, drilling on the Central Vietnamese margin, so far, has targeted mainly Miocene carbonates with a number of resulting oil and gas discoveries made.

This paper reports a combined study of the system of Neogene carbonate platforms flanking the basins offshore Central Vietnam analysed and presented by Fyhn et al. [26]. The study is based on approximately 13,000km

2-D seismic data tied to exploration wells (Fig.2). Seismic data range from vintage data acquired as early as 1974 to data acquired in 2003 constituting an open seismic grid with average line spacing ranging in between 3 - 40km. The seismic data quality varies. However, data generally has adequate resolution within the targeted Neogene carbonate successions with frequencies ranging from 20 - 50Hz corresponding to acoustic wavelengths in between c. 30 and 100m and a seismic resolution at best in between c. 7 and 25m.

The data document a very dynamic growth history of the carbonate system in the region. Factors such as regional Early Miocene transgression of structural highs along the Central Vietnamese margin combined with a warm climate probably catalysed massive carbonate platform growth. Onshore uplift and erosion linked with volcanism and associated inorganic nutrient pollution in the platform areas is interpreted as the primary mechanism governing the subsequent platform demise and drowning. The Cenozoic evolution of basins and highs together with Neogene volcanism and onshore uplift are therefore described initially before treating the Neogene carbonate growth.

2. Setting and structural framework

Cenozoic carbonates are widespread around the East Vietnam Sea, present from the Chinese margin in the north to offshore Borneo in the south [15, 17, 20]. In the south, platform growth began during Late Eocene and Oligocene time and locally continues to the present [4, 16, 18, 47, 74, 78]. Farther north along the Vietnamese and Chinese margins, widespread carbonate deposition initiated during the Early Miocene probably due to the absence of fully-marine conditions until the final stage of the East Vietnam Sea opening [21, 22, 26, 43, 44, 82, 83]. Oceanographic and climatic changes, terrigenous sediment supply, inorganic nutrient levels, volcanism, uplift and relative sea level fluctuations are factors interpreted to have had a significant influence on local and regional Neogene platform growth and demise in SouthEast Asia [19, 22, 26, 64, 80]. Carbonate platforms may therefore record information fundamental to unravelling the tectonic development of various regions and are useful indicators for local and global climatic and oceanographic changes.

2.1 Cenozoic basin development

Cenozoic basin development along the Central Vietnamese margin initiated through Paleogene rifting

[11, 21, 23, 39, 42, 59, 60, 87]. The exact timing of rift initiation is poorly constrained due to: 1) the scarcity of deep wells penetrating the oldest syn-rift succession and 2) the low biostratigraphic resolution of most of these non-marine rift systems. The significant crustal extension along the margin has been viewed in context with either the extension leading to the opening of the East Vietnam Sea and/or lateral movements along the Vietnamese margin linked with the India-Eurasia collision [21, 59, 70, 71] (Fig.1). The East Vietnam Boundary Fault Zone can be mapped seismically along the margin. In the study area it delineates the Quang Ngai graben - an elongated rift forming the southernmost extension of the Song Hong basin filled by Paleogene syn-rift deposits. The fault zone also delineates a coast-parallel Neogene depocentre and seems to have been a controlling lineament for the depositional system along this part of the margin (Fig.2).

Underlying the Tri Ton Horst to the Paracel islands (Figs.2 and 3) and adjacent basins are a number of grabens and half-grabens filled by tentatively dated Paleogene syn-rift deposits initially noted by Roques et al. [59] and Dang and Sladen [12]. Seismic resolution of the syn-rift succession on the uplifts is often only moderate, partly due to damping of the acoustic energy by the thick overlying carbonate succession. The Paleogene rift-system becomes more pronounced towards the Qiongdongnan and the Phu Khanh basins to the north and south filled by an up to several kilometres thick syn-rift succession confined to major grabens and half-grabens often measuring several tens of kilometres across (Fig.4).

The syn- and post-rift successions on and along the Tri Ton Horst are separated by an unconformity in places marked by distinct reflector truncations. The entire syn-rift succession tends to be strongly deformed and compressional deformation is tentatively interpreted in places affecting the top of the syn-rift succession (Fig.4). This may record a compressional pulse towards the end of the Paleogene possibly comparable to similar events in the Cuu Long and the northern Song Hong basins to the south and north, respectively [21, 58].

Kilometre-thick Neogene deposits deeply bury the syn-rift succession in large parts of the area. Farthest to the east, the thickness of the Neogene generally decreases due to the distal setting leaving Paleogene rift sediments and basement more shallowly buried. The kilometre-thick Neogene succession and the overall

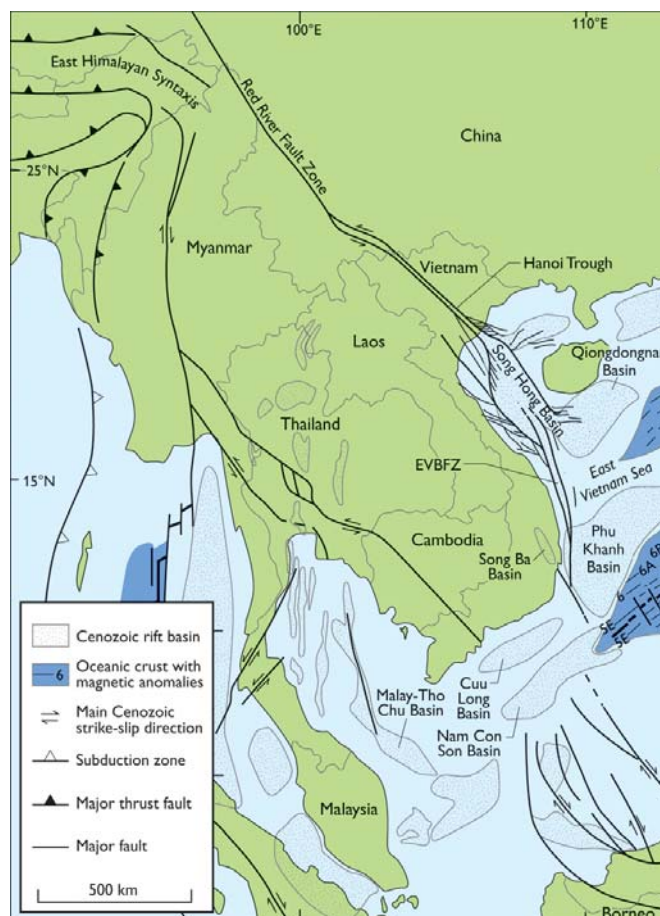


Fig.1. Map of Indochina and the western part of the East Vietnam Sea showing the outline of main basins and Cenozoic structures. EVBFZ: East Vietnam Boundary Fault Zone. Modified after Fyhn et al. [26]

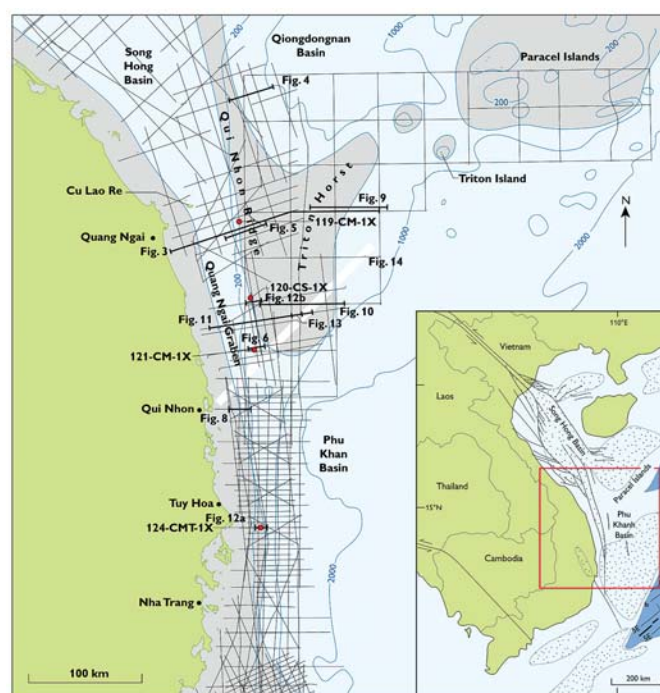


Fig.2. Map outlining the distribution of seismic and well data included in the study. Bold lines mark the position of illustrated sections. Bathymetry in metres. Modified after Fyhn et al. [26]

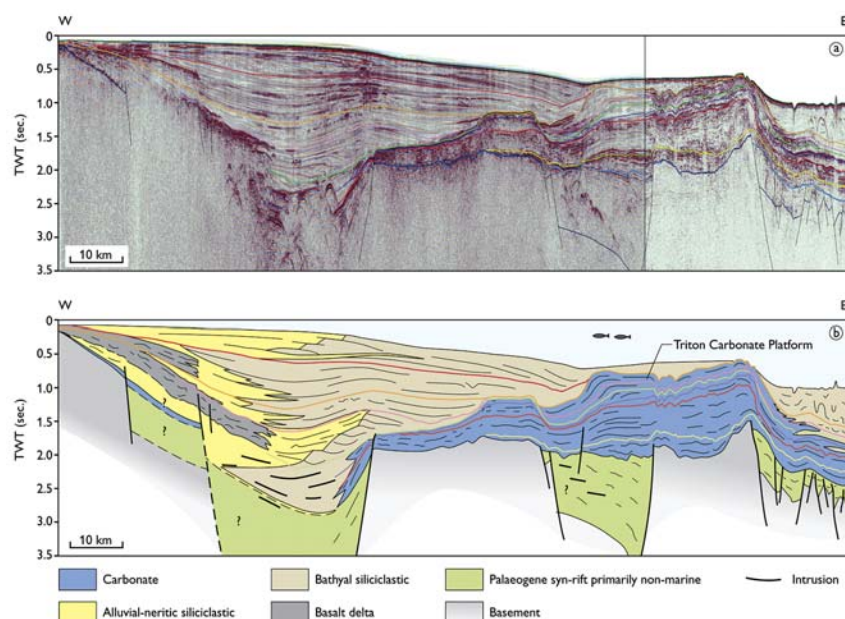


Fig.3. Regional seismic transect (a) across the Quang Ngai graben and the Quy Nhon ridge and Tri Ton Horst and corresponding stratigraphic interpretation (b). The transect illustrates the interplay between the growth and drowning of the Tri Ton Carbonate Platform and Neogene siliciclastic deposition and magmatism in the area. Carbonate growth peaked during the Early Neogene when terrigenous input was low. During the latter Neogene, carbonate growth retreated and eventually terminated concurrently with increasing siliciclastic input from the west, most likely associated with onshore uplift and magmatism. Location indicated on Fig.2. Modified after Fyhn et al. [26]

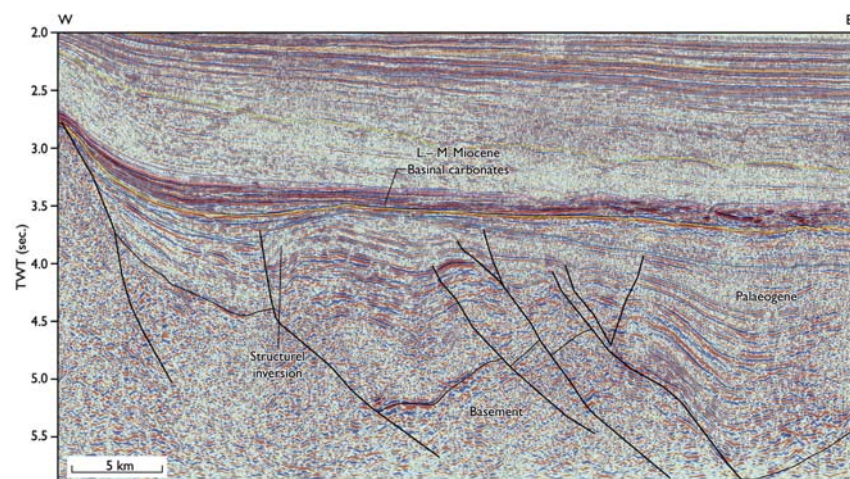


Fig.4. Seismic transect illustrating the Paleogene rift style in the area. Indications of late syn-rift to early post-rift compression are tentatively interpreted from the structural inversion observed on this transect. The inversion preceded Neogene carbonate growth and seems to have been accompanied by a period of moderate uplift and erosion judging by the unconformity capping the inversion structure. Location indicated on Fig.2. Modified after Fyhn et al. [26]

Neogene transgressive trend leading to the modern bathymetric outline of the area indicate the Neogene as a period of generally rapid subsidence.

The Neogene succession is dominated by siliciclastic deposits in the basin centres and to the west along the Vietnamese margin (Fig.3). The clastic sediments tend to

thin seaward on the Tri Ton Horst and in the Phu Khanh basin reflecting the increasing distance to the source areas.

2.2. Neogene volcanism and onshore uplift

The Upper Miocene through Pleistocene makes up the overwhelming majority of the siliciclastic strata in the region indicating an increase in siliciclastic deposition during the later part of the Neogene. This increase has previously been interpreted to reflect the coeval uplift and denudation of Central Vietnam and adjoining areas [9, 21, 22]. Although knowledge of the Neogene uplift of Central Vietnam remains fragmentary, denudation rates seem to have peaked during the Late Neogene similar to the offshore siliciclastic depositional rates [9].

The increased Late Neogene clastic input may in addition be linked with the climatic development during the period and to a lesser degree to erosion from uplifted areas farther away [11]. The northernmost part of the study area experienced latest Neogene southeastwards siliciclastic progradation induced by sediments spilling from the central Song Hong basin. Much of these sediments may be derived from regions farther away such as supplied by the paleo-Red River.

Basaltic volcanism took place in Central and South Vietnam from the Early - Middle Miocene onwards. The contemporaneous Late Neogene uplift has been attributed to igneous processes taking place in the region [9, 33]. Comparable Neogene magmatism was documented offshore in the

southern part of the study area [21]. Seismic and well data combined with the outcropping geology onshore and on small islands suggest the presence of Miocene to sub-recent extrusives along the Vietnamese margin in the northern part of the study area as well (Fig.3). Extrusives and intrusions in the area have been interpreted previously

and show close resemblances to similar magmatic successions imaged seismically e.g. along the North Atlantic margin [7, 21, 57] and are generally characterised by their strong upward confining reflections, beneath which the seismic signal strongly deteriorates.

Volcanoes appear as kilometre-wide knoll-features between a few tens to hundreds of milliseconds (TWT) high (Fig.6). Some volcanic edifices have well-defined concentric internal reflectivity whereas others display a more chaotic internal reflection pattern. Some volcanic edifices on seismic data resemble carbonate pinnacles. In the 121-CM-1X well a mounded feature was confused with a carbonate pinnacle prior to drilling, but drilling revealed a basaltic volcano probably of Middle Miocene age tentatively dated by apatite fission track analysis. The drilled volcano is interpreted as being mainly of submarine origin due to the presence of quench textures in the basalts and due to intercalation with marine sediments. Often, volcanic edifices distinguish from the local carbonate buildups and platforms either by their gravimetric/magnetic response or by the often very

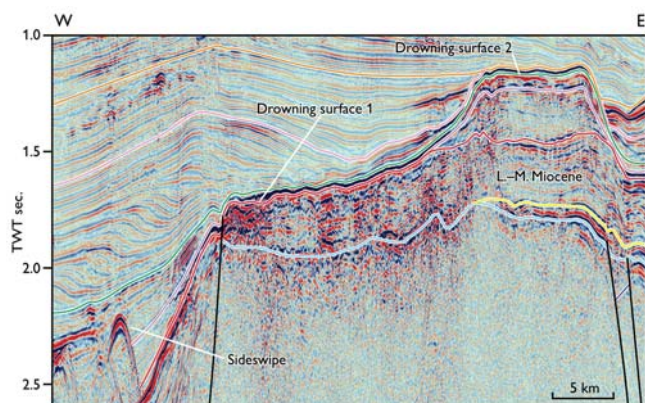


Fig.5. Blow-up of Fig.3 illustrating two platform drowning surfaces. Drowning surface 1 is base-lapped by a series of toesets. Location indicated on Fig.2. Modified after Fyhn et al. [26]

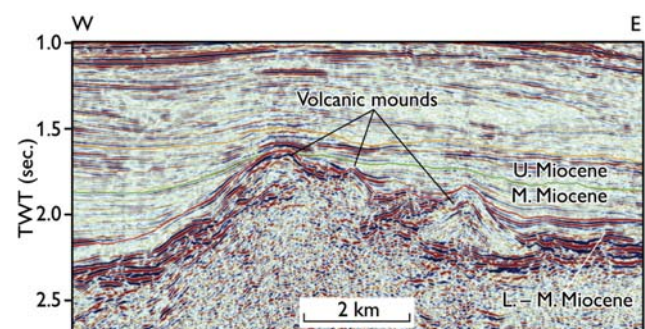


Fig.6. Miocene volcanic structures characterised by their mounded appearances. A comparable volcanic mound belonging to the same cluster of volcanoes was drilled in the 121-CM-1X well. Location indicated on Fig.2. Modified after Fyhn et al. [26]

chaotic internal and external appearance in contrast with the more organised architecture of the carbonate platforms along the margin. In contrast to carbonate platforms occupying structural highs, volcanic mounds mostly occur in basinal settings and were extruded down to several hundred metres below paleo-sea level as indicated by their relative position to coeval shelf breaks and carbonate platform margins.

Surrounding the Cu Lao Re island hosting an active volcano (Fig.2), numerous strongly reflected mounds immediately underlie the seafloor and thus suggest a similar volcanic origin.

Lava deltas are interpreted to fringe part of the margin. These often occur in areas where Upper Neogene basalts crop out along or near the present shore. The lava deltas are characterised by strongly reflected wavy or sub-parallel reflectors with upper surfaces conformable with overlying strata (Fig.3). Characteristically, the units show abrupt lateral terminations and seaward interfingering with moderate to well-reflective topset facies representing siliciclastic shelf deposits. The actual lateral terminations are characterised by subtle seaward inclined foresets interpreted as lava delta-fronts (Fig.3).

Strongly reflective sills were emplaced at various stratigraphic levels and occur concentrated in specific areas often associated with above-lying extrusives. The sills mostly parallel the adjacent strata but in places show sharp discordant cross-cutting relationships. Slight doming of the strata occurs above some sills and chimney-like features may exist above sills that tend to head into more shallow amplitude anomalies.

In one volcanic area to the north, stratigraphic reflectors are transected by numerous strong convex parabola-shaped reflections between 3 and 8km wide (Figs.3, 5). The reflections have similar phase on each limb of the parabola and cannot be explained as diffraction but are interpreted as sideswipes from steep-sided intrusions and/or volcanic mounds located next to the trail of the seismic transect.

3. Neogene carbonate growth

3.1. Early and Middle Miocene initial growth

Early Miocene carbonates form the oldest robustly dated drilled carbonates offshore Central Vietnam. The deepest drilled carbonate sections are likely of Burdigalian age although a slightly older Aquitanian age cannot be

ruled out due to insufficient biostratigraphic control. The deepest parts of the platforms tend to be made up by dolomites in contrast to the limestone-dominated upper part of the platforms.

Platform growth initiated on two major platforms; a platform fringing the Vietnamese coast referred to as the Tuy Hoa Carbonate Platform and a platform situated east of the Quang Ngai graben referred to as the Tri Ton Carbonate Platform (Fig.7a). The carbonates form the oldest Neogene deposits in the area and directly overlie the Mesozoic granitic basement, pre-Paleogene sediments and tentatively dated Paleogene non-marine deposits.

The oldest platform deposits signify a distinct Early Miocene regional transgression of the area. On the Tri Ton Horst, a thin undrilled deep succession onlaps the top of the syn-rift sequence. This may represent the initial inundation sequence recording the flooding of the ridge, which may have taken place during the Early Burdigalian and/or (?) Aquitanian time.

On the Tri Ton Carbonate Platform, the succession is fault confined along the Quy Nhon ridge and faults in places offset the deepest carbonates and influence the thickness of the platform deposits suggesting a slight continuation of faulting following the Paleogene in the area.

On the Tuy Hoa Carbonate Platform, increased platform thicknesses on hanging-wall blocks towards confining faults indicate rotational fault-block movement throughout the growth period. Extensional faults outline large parts of the platform margins and in places form the landward boundary of the Tuy Hoa Carbonate Platform suggesting that moderate faulting probably controlled the overall outline of part of the platform (Fig.8).

However, seismic resolution does not resolve the platform facies adequately and pinpointing the position of the platform margin is not possible everywhere. A detailed analysis of the internal platform facies of this interval is thus not possible based on the available data, and a clear distinction between platform and basinal carbonate facies was not accomplished in part of the study area. A very strong and generally continuous reflectivity typical for carbonates characterises the interval and is compatible with the reflection pattern of the overlying succession. In the Tri Ton area, the succession covers more than 40,000km² and is up to a few hundred metres thick in places.

In the southern part of the area, a distinct succession characterised by strong to very strong reflections makes up the off-platform deposits. These are interpreted to be composed of carbonate detritus shed from the platforms and basinal marls. Fyhn et al. [23] suggested these marls to contain organic rich intervals sourcing the Thi Nai lagoon seep oils occurring along the present coast near Quy Nhon. Biomarker analyses indicate marly source rocks for these oils [6, 72], and modelling suggests that the burial depth of the off-platform deposits and stratal dip of the overburden rocks are compatible with adequate maturation of the interval and shoreward migration of potentially generated oil [23].

The Quy Nhon ridge gradually became inundated and was buried by carbonates during Burdigalian time judging by the seismic pattern and the age of the oldest carbonates capping the ridge (Figs.3, 7a, b). In the following period carbonate growth concentrated on the Quy Nhon ridge and the Tri Ton Horst and a prominent platform margin was established outlining the margin of the structural highs towards the Quang Ngai graben and the Qiongdongnan and Phu Khanh basins (Fig.7b).

The platform interval corresponding to this period in places measures more than 600ms (TWT). This corresponds to more than 1km of Lower to Middle Miocene carbonates given an average acoustic velocity between c. 3.5 and 4.5km/sec comparable to that measured in available wells penetrating the Miocene carbonates in the area.

A well-developed carbonate apron flanks especially the eastern, southern and northern part of the Tri Ton Platform and grades basinward into an up to c. 500msec (TWT) thick interval characterised by high-amplitude, low-frequency, continuous reflections interpreted as deep-marine basin floor carbonates derived by gravity flows from the platform (Fig.9). Away from the platform, the basinal carbonates thin and intercalate with intervals distinguished by a more transparent seismic facies typical for deep-marine siliceous sediments [62] (Fig.9).

To the west in between the Tri Ton - and the Tuy Hoa Carbonate Platforms, a succession characterised by relatively high-amplitude, continuous reflections fills the lower post-rift part of the Quang Ngai graben. Drilling of the succession indicate a composition dominated by siliciclastic gravity flow sand- and siltstones [12].

On the Tri Ton Platform, a wavy and discontinuous reflection pattern characterises much of the Lower to

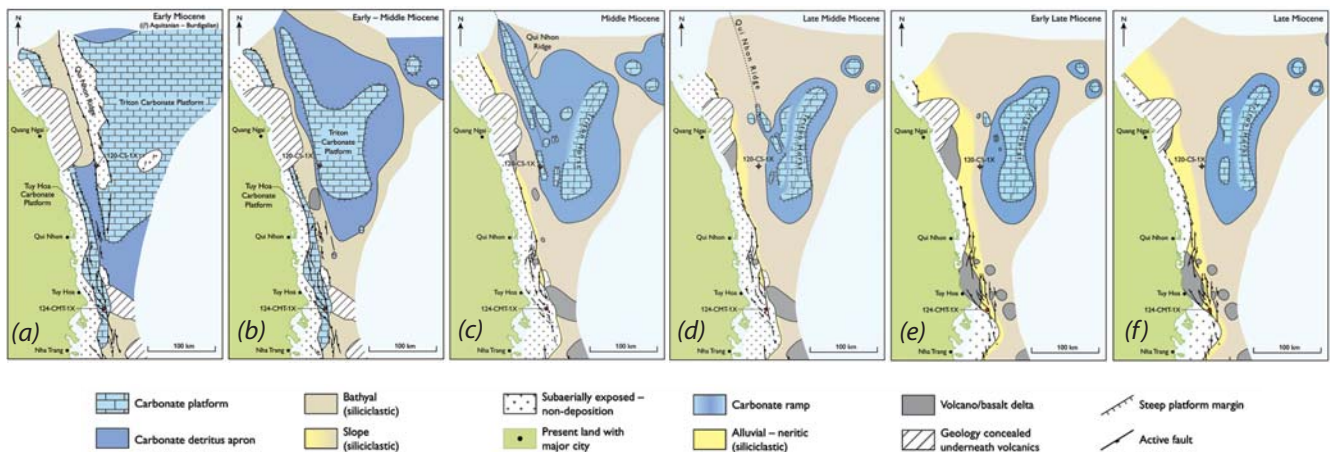


Fig.7. Paleogeographic maps based on seismic and well data. The maps represent the Early to Late Miocene development offshore Central Vietnam and reflect the interplay between carbonate platform growth, siliciclastic deposition and volcanism.

- a) Early Miocene: Burdigalian carbonates constitute the oldest carbonates drilled offshore Central Vietnam and overly basement and the Paleogene syn-rift. Slightly older, undrilled carbonates may exist in areas away from the most elevated part of structural highs. Deposition during the period reflects the initial transgression following Paleogene rifting when existing topography gradually became flooded
- b) Early - Middle Miocene: During Early to Middle Miocene time, all structural highs were inundated and carbonate growth focused on these elevated features. Carbonate detritus was shed far from the platform areas as carbonate production significantly exceeded the general creation of accommodation space on the platforms. Volcanism initiated during this period
- c) Middle Miocene: Partial platform drowning led to the break-up of the Tri Ton Carbonate Platform during the Middle Miocene. Farther landward, uplift resulted in subaerial exposure and termination of carbonate growth on the Tuy Hoa Carbonate Platform. Carbonate growth was replaced by fan-deltas along the paleo-Vietnamese margin sourced by the erosional products from the uplift. Volcanism increased significantly during the period
- d) Late Middle Miocene: Partial platform drowning continued on the Tri Ton Carbonate Platform during the late Middle Miocene restricting platform growth to the central part of the Tri Ton Horst and to a few satellite platforms persisting on the most elevated highs. Carbonate production was barely able to keep up with relative sea-level rise which resulted in drowning of the shoreward platforms and limited off-platform export of carbonate detritus
- e) Early Late Miocene: A number of satellite platforms drowned during the former period leaving only the central part of the Tri Ton Carbonate Platform and a handful of smaller isolated buildups to persist. The central part of the Tri Ton Carbonate Platform recovered after partially drowning during the former period, while the western satellite platforms drowned during the period
- f) Late Miocene: The remaining part of the Tri Ton Carbonate Platform struggled to keep up with relative sea-level rise but ultimately drowned during the Late Miocene. The area offshore Central Vietnam is presently dominated by siliciclastic deposition. Only sporadic carbonate growth takes place on restricted highs farthest to the east in the area. Modified after Fyhn et al. [26]

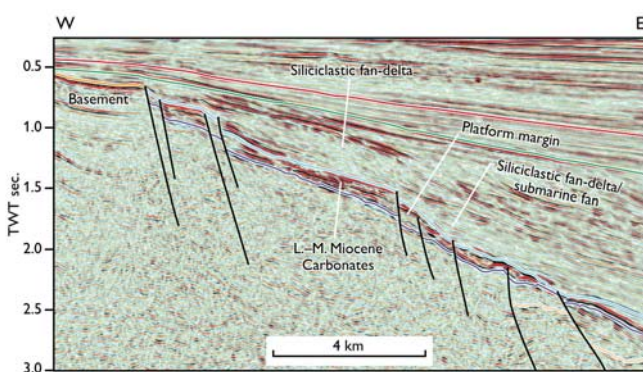


Fig.8. Transect across the Tuy Hoa Carbonate Platform. Normal faults outline the landward boundary of the carbonates and subtle faulting may also have confined the platform margin. Middle to Upper Miocene fan-deltas/submarine fans onlap the platform margin and buries the platform. Location indicated on Fig.2. Modified after Fyhn et al. [26]

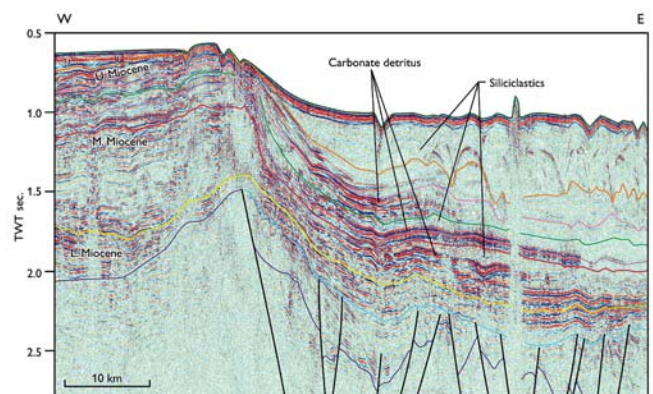


Fig.9. Carbonate detritus shed from the platform distinguishes from deep-marine siliciclastics by its strong reflectivity and intercalate with less reflective deep-marine siliciclastic sediments. Large amounts of Lower to Middle Miocene carbonate detritus formed compared to the subsequent period. Location indicated on Fig.2. Modified after Fyhn et al. [26]

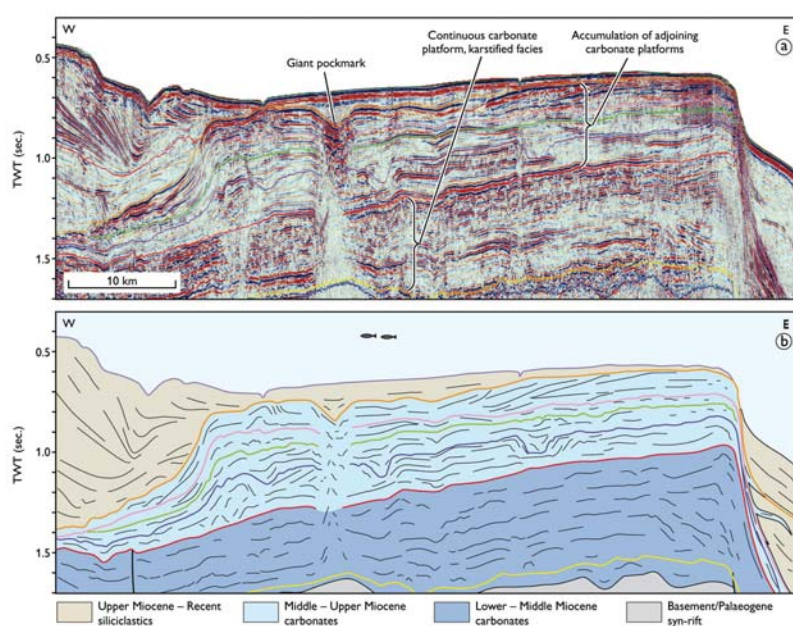


Fig.10. Seismic transect (a) across part of the Tri Ton Carbonate Platform and corresponding stratigraphic interpretation (b). Neogene platform growth offshore Central Vietnam took place in two consecutive phases. During the Early to Middle Miocene (corresponding carbonates marked in dark blue on Fig.10b), a discontinuous, strongly reflected seismic facies interpreted as karstified platform carbonates is common. During the subsequent Middle to Late Miocene period (corresponding carbonates marked in light blue on Fig.10b), the platform split up into discrete buildups with an internal reflection architecture suggesting very dynamic platform growth. The generally more continuous reflectivity suggests only modest karstification of most of the upper Middle to Upper Miocene carbonates compared to the former period. A prominent depression in the top-platform surface marks a giant collapse structure in the underlying carbonate succession. The collapse depression caps a chaotically reflected column in the underlying platform carbonates that in turn overlies a Paleogene fault zone. Location indicated on Fig.2. Modified after Fyhn et al. [26]

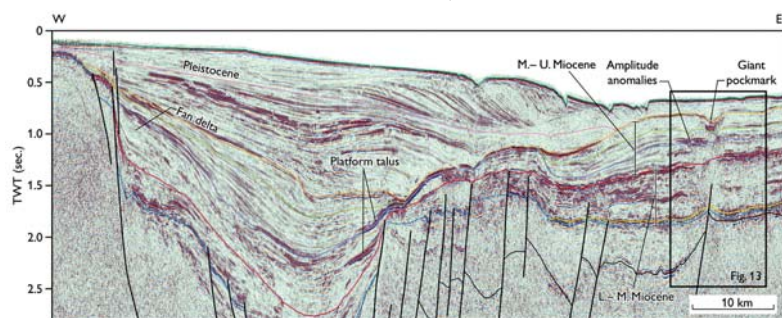


Fig.11. Seismic transect across the Quang Ngai graben and part of the Quy Nhon ridge. Platform carbonates dominate the Neogene succession in the east whereas terrigenous deposits prevail farther landward. Consequently, metres thick drowning sequences above Miocene Carbonate platforms grade into hundreds of metres thick siliciclastic successions to the west. Upper Middle Miocene to Quaternary siliciclastics in the west dominates volumetrically above Lower to lower Middle Miocene siliciclastic sediments and document a vast Late Neogene increase in terrigenous sedimentation. A Middle to lower Upper Miocene fan-delta fringe faults along the Quang Ngai graben in the west. Coeval basinal deposits farther east intercalates with platform talus towards the Tri Ton Carbonate Platform. The younger part of the Tri Ton Platform baselaps the older drowned part of the platform and is in turn gradually buried by prograding Upper Neogene siliciclastic deposits. A giant collapse scar marks the youngest drowning surface of the Tri Ton Platform to the east. A blow-up of the collapse scar is presented in Fig.13. Location indicated on Fig.2. Modified after Fyhn et al. [26]

Lower Middle Miocene succession (Fig.10). Together with the often relatively high reflection amplitudes this distinguishes the lower half of the Tri Ton Platform from the younger part (Figs.10, 11). The overall internal outline of the lower half of the Tri Ton Platform is characterised by parallel to sub-parallel strata apart from along the platform margin. Along the platform margin, aggradation and very limited progradation characterise the reflection pattern (Fig.10).

The wavy and discontinuous reflection pattern together with the often relatively high reflection amplitudes characterising much of the lower Tri Ton Platform resembles karstified parts of other Miocene carbonate platforms in the East Vietnam Sea [4, 22, 31, 46, 74]. The lower part of the Tri Ton Carbonate Platform is therefore interpreted to have been affected by repeated periods of subaerial exposure and moderate leaching, which is in accordance with karst induced caverns and enhanced porosity interpreted in wells that resulted in instantaneous drilling mud-losses associated with intervals of enlarged drill hole calibres. In addition, the presence of small patch reefs may contribute to the wavy and discontinuous reflection pattern of this part of the platform and other diagenetic effects may have contributed to part of the reflector brightening.

To the west, the Lower to lower Middle Miocene Tuy Hoa Carbonate Platform constitutes an up to many hundreds of metres thick, clean carbonate succession that is generally characterised by very strong, low-frequency internal reflectors (Figs.8, 12a). The top of the carbonates is emphasised by a very strong “hard-kick” reflection that erosionally truncates the underlying carbonates and marks a pronounced downwards acoustic impedance increase (Fig.12a). Only in the northern part of the Phu Khanh basin is a steep platform margin recognisable. Farther south, more extensive erosion

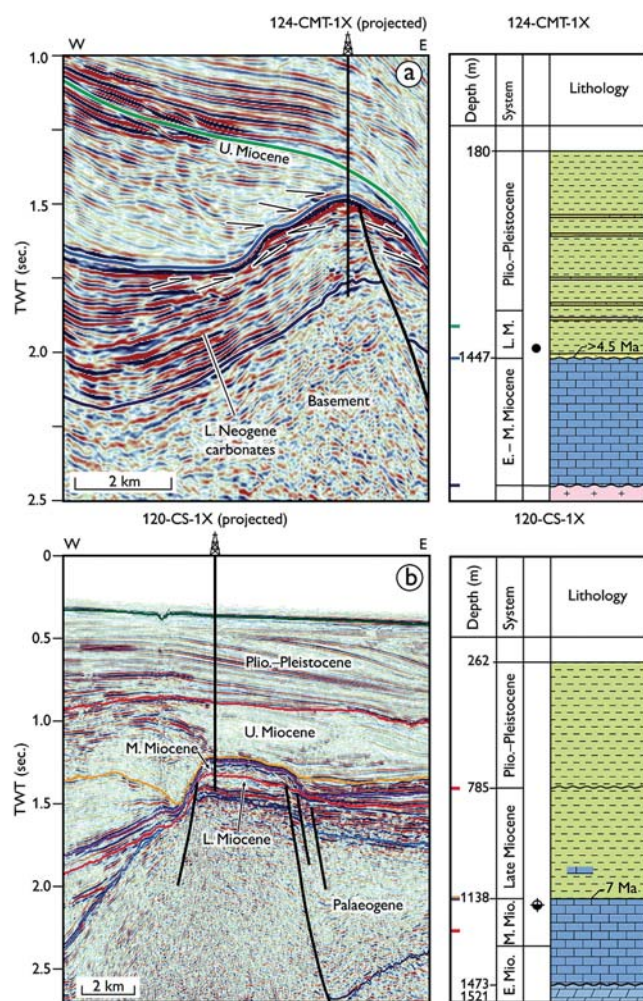


Fig.12. Miocene carbonates have been the primary target for exploration drilling offshore Central Vietnam so far with a number of oil and gas discoveries made in Lower to Middle Miocene carbonates. a) 124-CMT-1x targeted Lower to Middle Miocene shallow water carbonates and is the first of only four wells drilled in the Phu Khanh basin (at the time of writing). The well transected an oil column with two net pay intervals totalling approximately 20 metres in thickness. The distinct top-carbonate unconformity formed in response to protracted subaerial uplift and represents a hiatus spanning at least 4.5Ma. 124-CMT-1x stratigraphy modified after Johansen (2011). b) The 120-CS-1x well tested intermediate to shallow water Lower to Middle Miocene platform carbonates. The buildup drowned during the Middle Miocene but was only buried ca. 7Ma latter by siliciclastic deposits. Intersecting depths to seismic horizons are indicated on the left side of the well logs. Location and well positions are projected on Figs.2 and 7. Modified after Fyhn et al. [26]

envisaged by pronounced reflector truncation probably resulted in alteration or complete destruction of the original geomorphologic outline of the platform.

The erosional unconformity capping the Tuy Hoa Platform spans much of the Middle and Late Miocene, and reflector truncation suggests widespread

erosional removal of as much as a few hundred metres of platform carbonates. Wedge-shaped sedimentary bodies interpreted as siliciclastic fan-deltas and submarine fans characterise the strata immediately post-dating the Tuy Hoa carbonates in places. The oldest of these wedges occurs seawards of the Tuy Hoa carbonate Platform and onlaps the lower part of the platform slope and thus together with the prominent erosional unconformity capping the platform suggests a significant fall in relative sea level (Fig.8). The hiatus therefore seems to have formed in response to subaerial uplift probably linked with faulting and lithospheric heating associated with magmatism since voluminous volcanics of that age occur widely in the area (Figs.7b - e).

3.2. Middle and Late Miocene phased platform drowning

Most of the Tuy Hoa Carbonate Platform remained subaerially exposed for more than 4Ma during the rest of the Middle Miocene as suggested by the hiatus dated in wells and seismic stratigraphy (Fig.12a). The platform area was reflooded during the Late Miocene, but platform growth did not resume regionally in the area. Middle and Late Miocene carbonate deposition was thus restricted mainly to the Tri Ton Horst and the Quy Nhon ridge farther to the east (Figs.7c - f).

During the Middle Miocene, the Tri Ton Carbonate Platform stepped back and split up into a number of separate platforms as a result of partial drowning (Figs.5, 7c - f). Middle Miocene partial drowning especially affected the area in which the Tri Ton Horst and the Quy Nhon ridge merge. As a result, carbonate growth continued on two isolated platforms occupying the central parts of the Quy Nhon ridge and the Tri Ton Horst as well as on a number of smaller buildups in between the two larger platforms.

A few tens of metres thick condensed hemipelagic pyritic and slightly calcareous mudstone succession caps the drowned Lower to Middle Miocene Platform carbonates. Well data suggest that the succession was deposited throughout a more than 7Ma long Middle to Late Miocene period. In places the condensed sequence caps a very hard silicified platform crest drilled by exploration wells that probably formed in response to a protracted period of non-deposition. The succession is interpreted as a drowning sequence covering part of the Tri Ton Platform (Fig.5).

Off the platform in the Quang Ngai graben, the drowning sequence thickens and is represented by an eastwards prograding, siliciclastic mudstone-dominated succession several hundred metres to more than one kilometre thick (Fig.5).

In the north, the lower part of the Middle - Upper Miocene carbonates covering the Quy Nhon ridge as well as the smaller isolated platforms immediately to the south are characterised by a seismic facies made up by low-frequency, moderately continuous to discontinuous reflectors showing intermediate to very high reflection amplitudes (Fig.10a). An overall aggrading build-up pattern characterises these platforms (Fig.10b), although a few kilometres of progradation took place locally following early subtle platform back-steps.

Strongly reflected platform aprons radiate a few kilometres westwards from these platforms where they intercalate with basin floor siliciclastic deposits imaged by much weaker higher frequency reflectors (Fig.11). Towards the east, platform aprons merge with the much thicker and more extensive developed aprons radiating from the carbonate platform(s) occupying the Tri Ton Horst (Figs.7c - d, 11).

The siliciclastic sediments in the west intercalated with platform talus constitute the basinal part of an eastwards prograding siliciclastic succession. Well-developed clinoform topsets, foresets and toesets separate the siliciclastic sediments into shelf, shelf-slope and basinal deposits (Fig.11). The lower part of the succession is genetically linked with a coast-parallel fault system confining a well-developed fan delta system. Offshore Quang Ngai and farther south, the siliciclastic deltaic system intercalates with a volcanic delta (Fig.3).

During the later half of the Middle Miocene, the carbonate platforms occupying the Quy Nhon ridge and the area immediately to the south eventually drowned (Fig.7c - e). For a limited period of time, a couple of smaller buildups managed to keep pace with relative sea-level rise by backstepping and aggradation. However, these too eventually succumbed to drowning during the latest Middle to Early Miocene time.

Farther east, during the later half of the Middle Miocene and the Late Miocene, the platform(s) thriving on the Tri Ton Horst managed to keep up with relative sea-level rise. The reflection pattern on these eastern platforms are characterised by intermediate to strong

reflections that in general are somewhat weaker than the underlying Lower to lower Middle Miocene succession (Figs.10, 11). Moreover, the reflections tend to be slightly more continuous than the older carbonates.

Compared with the initial Lower - Middle Miocene platform on the Tri Ton Horst, the subsequent Middle to Upper Miocene platform architecture was characterised by a substantial intra-platform relief signified by the presence of smaller buildups (a few kilometres in diameter and c. 100 - 200m high) separated by channels and intra-platform deeps that together make up the greater platform area of especially the eastern and largest part of the Tri Ton Platform area (Fig.10). However, the available open seismic grid does not adequately resolve the spatial and temporal outline of these sub-platforms, and more detailed mapping is required.

Characterising the four mapped later Middle to Late Miocene sub-stages, up to three considerable platforms, each covering in between 500km² to more than 2000km², were recognised on the Tri Ton Horst (Figs.7d - f). Externally, these platforms were confined most frequently by hundreds of metres high, steep margins that became higher and steeper through time. In contrast, ramp-like margins outline most of the internal margins facing neighbouring platforms on the Tri Ton Horst (Figs.7d, f). Fast and rapidly changing progradation and aggradation resulted in continually alternating platform outlines throughout the period.

The relative volume of the distinct high amplitude talus aprons fringing platforms towards the east substantially reduced during the Middle Miocene as compared with the previous period, and continued to decrease throughout Middle and Late Miocene time (Figs.3, 9). West of the Tri Ton Horst, substantial volumes of talus aprons fringe the carbonate platforms. The aprons radiate up to c. 20km from the platform margins and intercalate with the more modest talus aprons of the western platforms, and within the uppermost Middle to Upper Miocene baselap the flanks of drowned platforms in the west (Figs.3, 11). In contrast, the coeval talus aprons from the westernmost platforms only radiate less than 5km off the platform margins and rapidly thin to close to the brink of seismic resolution.

The youngest Upper Miocene part of the platform carbonates is buried underneath an up to a few hundred metres thick low-reflective to semi-transparent mainly Pleistocene succession interpreted as hemipelagic deep

marine deposits (Fig.10). Farther east, the platform margin in places subcrops the modern seafloor at 400 - 500m depth (Fig.3). This suggests final drowning of the Tri Ton platform carbonates sometime during the Late Miocene thus documenting eastwards younging platform drowning ages.

East of the Tri Ton Horst, isolated platforms capping structural highs survive to the present day. These platforms constitute prominent elevated features surrounded by several hundred metres deep water that form the basis of the Paracel Islands. However, seismic data suggest a number of guyots - flat-topped seamounts - interpreted as drowned carbonate platforms located in several hundred metres of water depth thus indicating that Late Neogene platform drowning affected this area as well.

3.3. Giant buried craters

Peculiar depressions form up to a few hundred metres deep scars in the upper surface of the carbonate platform overlying the Tri Ton Horst (Figs.10, 11). The depressions are up to a few kilometres wide and often filled with Late Neogene siliciclastic sediments (Fig.13). The features overly poorly to chaotically reflected columns of platform carbonates. The upper part of these columns frequently contains very strong reflections whereas the underlying levels appear semi-transparent. Concave upwards reflectors frequently signify the upper part of these columns whereas up-warping of deeper platform reflectors occur along the flanks of the deeper parts of the columns.

The depressions are interpreted to represent giant pockmarks associated with Late Neogene areally restricted "cave-in" of underlying carbonates. The concave upward pattern within the upper part of these features reflects the collapsed material itself often amplified by velocity pull-down associated with the siliciclastic deposits filling-in the collapse craters. The up-warps of the reflectors along the deeper flanks of the columns are more enigmatic. They could reflect drag structures related with injection of fluids from below. However, it cannot be ruled out that the up-warps represent strong velocity pull-ups beneath highly cemented parts of the carbonate platform that more than compensates for any velocity pull-down associated with the siliciclastic in-fill of the sink holes above.

Comparable giant pockmarks exist entirely within the carbonate platform overlying the Tri Ton Horst. In these

cases the collapse-induced relief was mainly buried by Middle to Late Miocene platform carbonates testifying to slightly earlier collapse.

The observed depressions often overlie deeper seated basement cored faults possibly indicating a relationship to the structural setting. Furthermore, amplitude anomalies (mostly "soft kicks") regularly occur within the collapse zone or within the carbonates flanking the vertical collapse columns. This could reflect either anomalous fluid content within and next to the zones or diagenetic effects.

The above observations may indicate that the giant pockmarks formed in response to localised massive subsurface carbonate dissolution and fluid venting occurring mainly during the Late Neogene. Although

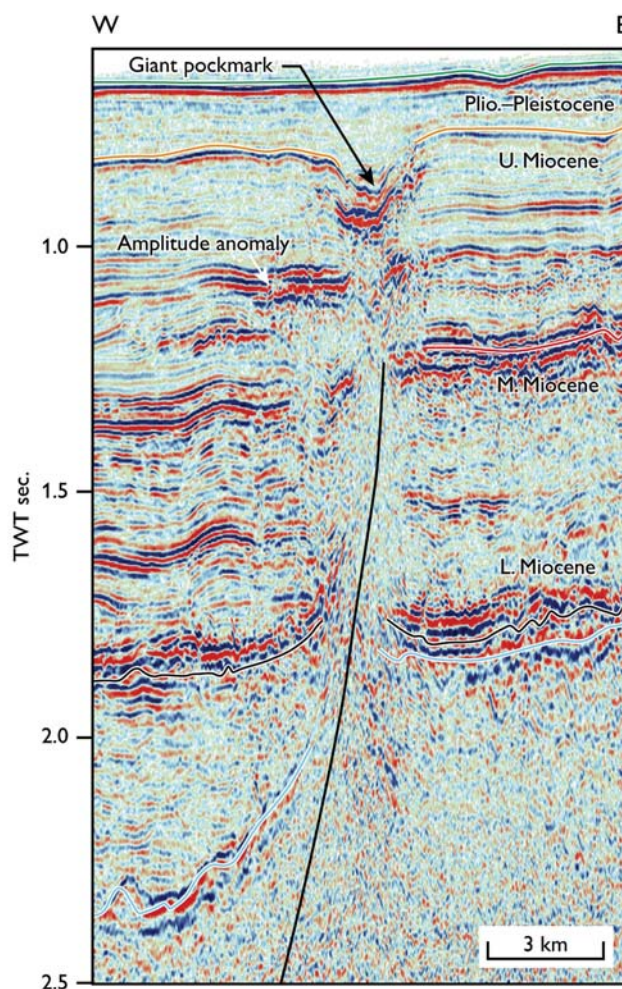


Fig.13. A giant pockmark marks the top of the Tri Ton carbonate Platform and is filled by Plio-Pleistocene siliciclastic deposits. The giant pockmark caps a chaotically reflected column that overlies a Paleogene fault zone. Amplitude anomalies flank the collapse zone. Location indicated on Figs.2 and 11. Modified after Fyhn et al. [26]

controversial, the mechanism responsible for dissolving such massive volumes of carbonates and creating these massive craters is speculated to be CO₂- and/or methane-enriched fluid venting compatible with the venting taking place within the central Song Hong basin immediately to the north.

The region is notorious for the occurrence and accumulations of CO₂ derived from either mantle or crustal sources or a combination of the two [36]. Together with the presence of soft-kicks along the collapse features that could reflect trapped CO₂ in the subsurface this supports the genesis of the giant pockmarks considered above. Moreover, densely spaced giant pockmarks in the area immediately to the east of the Tri Ton Horst records an active fluid circulation system which likely relates to either seepage of CO₂ or hydrocarbons [68].

However, hydrothermal circulation and venting guided by pre-existing faults associated with e.g. deeper seated intrusions cannot be ruled out as the cause for the giant pockmarks. Deep-burial carbonate dissolution has in some cases previously been attributed to hydrothermal circulation focused along faults [14, 32], Esteban & Taberner, 2003. Late Neogene magmatic activity is documented regionally by the presence of volcanic mounds, basalt deltas and intrusions.

The collapse features show some striking similarities with hydrothermal vent complexes along the British and Norwegian Atlantic margin [30, 37, 57]. Similar to the observed Vietnamese features, the North Atlantic vent complexes are characterised by distinct several tens to hundreds of metres deep craters between a few hundred metres and 11km in diameter underlain by chaotic reflected fluid conduits and diatremes. Both up-warping and down-warping of strata occur along the flanks of these North Atlantic hydrothermal conduits, and amplitude anomalies along their flanks are common [57] similar to what is observed on the Tri Ton Ridge.

In contrast to the Vietnamese features, most - but not all - hydrothermal vent craters reported are associated with sediment/volcaniclastic cones filling in the craters, extruded during the final stage of venting [30, 37, 57, 69]. However, these vent complexes formed in siliciclastic dominated basins speculated to be more prone to mechanical remobilisation of subsurface sediments. In contrast, dissolution and hydrothermal karstification could be more common in the Tri Ton Ridge area dominated by carbonates.

None the less, and in contrast to giant pockmarks induced by magmatic activity in other parts of the world, no magmatic intrusions have been demonstrated directly beneath the collapse features on the Tri Ton Ridge. Hence, CO₂ - and/or methane-enriched fluid venting not directly linked with magmatism are considered most plausible to explain the observed giant pockmarks.

4. Discussion and mechanisms governing platform growth and demise

The regional distribution of thick Lower and Middle Miocene carbonates testify to a depositional environment favourable for carbonate platform growth including a suitable and subsiding substrate promoting nucleation of carbonate growth, warm tropical climate, low terrigenous and nutrient input and optimal oceanographic conditions [26]. The clean Lower and Middle Miocene carbonates of the Tuy Hoa Carbonate Platform fringing Vietnam's paleo-shores and of the Tri Ton Carbonate Platform support low terrigenous input into the area, although the sand and silt dominated Lower Neogene succession within the Quang Ngai graben document coeval siliciclastic supplies to the area (Fig.14). It is noteworthy, however, that the Lower Neogene basinal siliciclastic sediments are distinctly coarser than the overlying Upper Neogene basinal deposits in the one well penetrating this succession [12]. These relatively coarse grained deposits may be more widely distributed judging by the distinct seismic reflection pattern of this interval. This may be an indication of a variation with time not only in terms of the supplied volume of terrigenous sediments but also in the nature of these. Furthermore, this could together with the very clean carbonates of the Tuy Hoa platform along the margin indicate more restricted point sourced terrigenous supplies to the basinal areas during the Early Neogene in contrast to the Late Neogene.

Following the initial Early Miocene transgressive phase, carbonate growth stabilised on the most prominent structural highs (Figs.7b, 14). The outline of the Lower to lower Middle Miocene part of the Tri Ton Carbonate Platform indicates that carbonate deposition took place on a coherent large platform with only moderate internal relief. The aggradation and progradation along the platform margin suggest that Early to early Middle Miocene platform growth kept pace with the creation of accommodation space. The well-developed platform apron and the significant export of carbonate detritus to the basin areas indicate a substantial surplus of carbonate

production and a consequent keep-up style of deposition during the Early to early Middle Miocene on the Tri Ton Platform. This is in accordance with the signs of repeated periods of karstification, since even moderate relative sea-level fluctuations on such platform would have resulted in recurring subaerial exposure events.

The above observations and the up to more than one kilometre thickness of the Lower to lower Middle Miocene carbonate successions encountered on the Tuy Hoa and Tri Ton Carbonate Platforms suggest substantial regional carbonate production and a rapid platform accumulation generally in the order of 100 - 200m/My throughout the period in areas with the highest rates. This seems to support the notion of favourable growth conditions during the Early Neogene.

The deterioration of the carbonate system in the study area seems to have initiated during the later half of the Middle Miocene (Fig.14). Platform termination on the Tuy Hoa Carbonate Platform was coeval and linked with the protracted Middle to Late Miocene subaerial uplift affecting a large fraction of the Vietnamese margin.

In contrast, the Tri Ton Carbonate Platform succumbed to drowning following a protracted period of Middle and Late Miocene partial drowning and recovery events. However, the fundamental cause of this gradual platform demise remains cryptic.

Carbonate platforms drown when relative sea-level rise exceeds the rate of carbonate accumulation bringing platforms beneath the euphotic zone of rapid carbonate production [65]. Factors considered to promote platform drowning include: 1) rapid pulses of relative sea-level rise, 2) slowed platform growth induced by deterioration of the carbonate production and accumulation potential and 3) over-steepening and self-erosion of platform margins [65, 66, 81].

A number of factors strongly impact carbonate production and accumulation rates. These include variation of sea-surface temperatures, inorganic nutrient levels and terrigenous/volcaniclastic input as well as variation of other factors such as ocean chemistry including surface water pH and salinity [67]. Increased terrigenous/volcaniclastic input and decreasing sea-surface temperatures (within the most common temperature range) tend to reduce carbonate production [61, 67, 77, 79]. Increased sea-surface inorganic nutrient levels similarly tend to decrease the overall rate of carbonate production and further may act to decrease

the carbonate accumulation potential due to enhanced bioerosion [28, 29, 48].

The initiation of partial drowning in the Middle Miocene on the Tri Ton Carbonate Platform occurred at the same time as regional magmatism intensified and terrigenous supplies to the basins substantially increased (Fig.14). Even so, clean carbonates make up virtually the entire platform succession including the youngest part. This does not support increased siliciclastic supplies or volcanic input to the platform area during the later growth stages. Moreover, biostratigraphic evidence from the thin hemipelagic siliceous succession capping the platform document condensed deposition during a more than c. 7Ma long period (Fig.8b). This precludes increased siliciclastic sedimentation across the Tri Ton Platform during the period and thus rules out increased siliciclastic supplies to the platform area or volcanism as direct stressing factor leading to platform drowning.

The Miocene was a period of rapid climatic changes; and global temperatures started dropping during the Middle Miocene [41, 84]. At the same time, glaciations and deglaciations in higher latitudes resulted in significant sea-level fluctuations [45]. Moreover, Miocene monsoon intensification affected the SouthEast Asian climate and probably influenced oceanographic conditions [10, 22, 75,

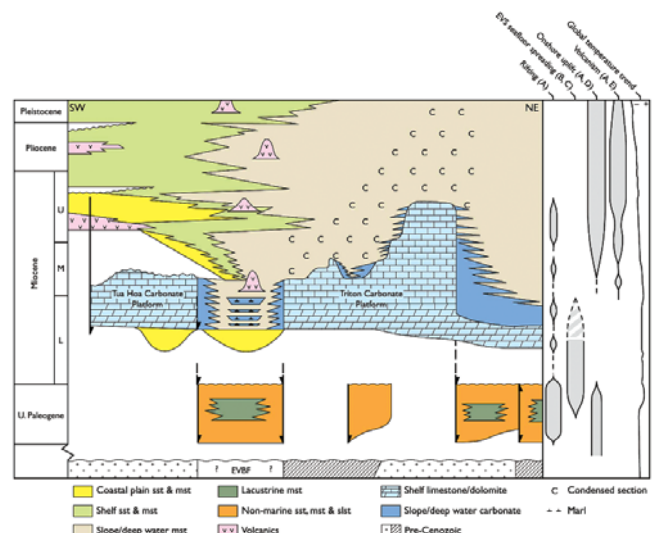


Fig.14. Stratigraphic chart illustrating the overall depositional development together with the timing of the main regional geologic events and the smoothed relative global temperature trend after Zarchos et al. [84] based on the δO^{18} -ratio of deep-marine benthic foraminiferous. A: Fyhn et al. [21]; B: Briaies et al. [8]; C: Barckhausen and Roeser, [2]; D: Carter et al. [9]; E: Lee et al. [39]. EVS = East Vietnam Sea; EVBF = East Vietnam Boundary Fault; mst = mudstone; slst = siltstone; sst = sandstone. Approximate transect location indicated on Fig. 2. Modified after Fyhn et al., [26]

86]. These global and super-regional climate changes may have acted to stress carbonate production on the Tri Ton Carbonate Platform during Middle and Late Miocene time.

However, partial platform drowning seems to have initiated in the west and progressed eastwards (seawards) throughout the Late Neogene, and modern carbonate growth continues farther east around the Paracel Islands. This pattern does not support climatic deterioration as the primary cause for platform drowning. Instead, the seawards migrating drowning trend could indicate a deterioration of the growth environment linked with factors rooted in the onshore coeval evolution.

Comparable regional platform drowning events elsewhere in the East Vietnam Sea has been attributed to increased inorganic nutrient supplies to platform areas associated with coastal run-off and increased terrigenous input to the basinal areas [19, 22, 37, 63].

This study documents a similar substantial increase in terrigenous supplies to the area immediately landwards from the Tri Ton Carbonate Platform occurring simultaneous to the onset of platform drowning offshore Central Vietnam (Fig.14). There seems to be a good correlation with this seawards migrating trend of platform drowning and the coeval progradation of the shelf and by inference increasing input of inorganic nutrients.

Combined with climatic deterioration and fluctuating sea level, offshore increased inorganic nutrient input derived mainly from Central Vietnamese uplift and denudation is thus interpreted as the most plausible cause for Neogene carbonate platform drowning. Future high-resolution geochemical studies and microfacies analysis of the late-stage growth intervals and overlying drowning sequences of the Tri Ton Platform may help test this hypothesis of nutrient pollution as carbonate growth-inhibitor offshore Central Vietnam.

6. Conclusions

A Danish-Vietnamese earth scientific research initiative, the ENRECA project, has been ongoing for almost 20 years. During the course of the project, the Vietnamese geology and petroleum potential has been investigated. A highly diversified basin-analytical programme has been carried out and is exemplified in this paper by the investigation of Miocene carbonate growth and demise along the Central Vietnamese margin.

Miocene carbonate deposition was widespread on structural highs offshore Central Vietnam. Platform

carbonates cover several tens of thousands of square kilometres and constitute an important exploration target in the area with hydrocarbons sourced mainly from Paleogene lacustrine syn-rift shales and humic coals, although a Miocene marine marl source rock may also contribute to the petroleum systems of the area.

Platform growth initiated probably in the Burdigalian during the transgression associated with the final opening of the southwestern part of the East Vietnam Sea and promoted by the transgressed relief left behind after Paleogene rifting.

Between Early and Middle Miocene time, platform growth thrived regionally with high carbonate production rates presumably encouraged by favourable climatic and oceanographic conditions and low terrigenous and nutrient input to the platform areas.

From Middle to Late Miocene time, carbonate growth retreated seawards and repeated periods of partial drowning and platform breakup took place.

Contemporary with platform retreat and breakup, the Vietnamese mainland was uplifted triggering rapid denudation. This resulted in a pronounced increase in terrigenous detritus being shed into the offshore basins, and caused subaerial exposure and termination of the Tuy Hoa Carbonate Platform fringing the Central Vietnamese margin. The regional uplift could be linked with the coeval magmatism and was likely associated with distinctly increased inorganic nutrient supplies to the platform areas farther offshore sourced from the mainland. The elevated nutrient input polluted the platform areas and possibly combined with climatic deterioration stressed carbonate production resulting in platform split-up and partial drowning.

Stressed carbonate growth conditions led to drowning of the remaining part of the Tri Ton Carbonate Platform during the Late Miocene. However, small-scale platform growth continues to the present farther offshore around the Paracel Islands isolated from terrigenous nutrient pollution.

A number of giant pockmarks characterise the final drowning surface of the Tri Ton Carbonate Platform and the youngest carbonates below. The giant collapses could be interpreted as the effects of subsurface carbonate dissolution and mobilisation associated with hydrothermal circulation and venting. Alternatively, carbonate dissolution could have been induced by either CO₂ - enriched fluids or acidification caused by biodegradation of hydrocarbons.

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The presented results have been achieved through long-term research cooperation between the "twinning" research institutes of Vietnam Petroleum Institute (VPI) and the Geological Survey of Denmark and Greenland (GEUS), on the one hand, and Hanoi University of Mining and Geology (HUMG), Hanoi University of Science (HUS) and the Department of Geosciences & Natural Resource Management, University of Copenhagen, on the other.

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STRATIGRAPHIC CORE WELLS ENRECA-1, -2 AND -3: RESULTS OF THE SONG BA RIFT, PHU QUOC ISLAND AND BACH LONG VI ISLAND DRILLING CAMPAIGNS

Lars H.Nielsen¹, Michael B.W.Fyhn¹, Henrik I.Petersen^{1*}, Jussi Hovikoski¹, Jens Therkelsen¹, Hoang Anh Tuan², Ngo Kieu Oanh²

Nguyen Hong Minh², Hoang Manh Tan², Bui Thi Ngoc Phuong², Phan Van Thang², Chu Duc Quang², Ioannis Abatzis¹

¹Geological Survey of Denmark and Greenland (GEUS)

^{1*}Former GEUS, now Maersk Oil & Gas, Copenhagen, Denmark

²Vietnam Petroleum Institute

Email: lhn@geus.dk

Summary

The long-term research co-operation between Vietnam and Denmark within basin analyses has generated many significant results. These have been used intensively in many ways including assessments of the hydrocarbon potential of the offshore basins, as input for license rounds, for promotion campaigns to attract industrial interest and for the publication of numerous scientific papers and presentations, which have contributed to the international appreciation of the fascinating geology of Vietnam.

Beside an extensive capacity building programme, one of the main activities of the ENRECA-programme has been the drilling of three stratigraphic core wells that have provided the research team with continuous cores of excellent quality, which have been analysed for sedimentary facies, source rock potential, age, petrography and reservoir properties.

The ENRECA-1 core-well was placed in the continental Song Ba rift in central Vietnam and cored 478m of the Oligocene (?) - Miocene fill of the rift. The cores document the variable depositional environments of the rift-fill. The most significant finding is the presence of two excellent lacustrine source rock successions, which have bearings on the occurrence of potential source rocks in the offshore Phu Khanh basin and thus the hydrocarbon potential of the basin.

The ENRECA-2 well was placed on the Phu Quoc island, where it cored 500m of Lower Cretaceous strata. The cores demonstrate the dominance of fluvial sandstones which in places show fair reservoir properties. Interbedded variegated mudstones were mainly formed in oxygenated lakes and flood plains and contain mostly inert organic matter.

The drilling of the ENRECA-3 well fulfilled an early proposal of coring the promising source rock bearing succession exposed in the Neogene inversion structure that forms the Bach Long Vi island. The cores document the presence of a minimum of 233m of excellent, world class oil-prone Palaeogene lacustrine source rocks. The source rocks are interbedded with various density current flow deposits including turbidites, hybridites and debrites, which together with sandstone dykes form an effective drainage system for hydrocarbons that may be generated where this prolific succession is deeper buried and matured.

The three strategically placed ENRECA core wells thus provided significant new insight that is discussed below.

The signing of a new Memorandum of Understanding (MOU) between VPI and GEUS will give the opportunity to their joint ENRECA research team to continue providing reliable and "demand-driven" research services to the public and industry in the years to come.

Key words: ENRECA-1 well, ENRECA-2 well, ENRECA-3 well, Song Ba rift, Phu Quoc island, Bach Long Vi island.

1. History of research co-operation

The Vietnam Petroleum Institute (VPI) and the Geological Survey of Denmark and Greenland (GEUS) have been the core institutes in a long-term research programme between Vietnam and Denmark within basin analysis. Furthermore, the Hanoi University of Science (HUS), the Hanoi University of Mining and Geology (HUMG) and the Department of Geosciences & Natural Resource Management, University of Copenhagen (ING), have also been participating in this co-operation.

The programme was initiated by a visit to GEUS in

1993 by CCOP-representatives (Co-ordinating Committee for Geoscience Programmes in East and Southeast Asia) who investigated the possibility of co-operation within research capacity development in the CCOP-countries [20]. Funding was obtained from the Danish Energy Authority (DEA) and the first joint project between VPI and GEUS began in 1995. A need for interpretation tools at VPI was identified, and modern facilities were installed in 1996 with support from the Danish International Development Assistance (Danida). Following the successful completion of the project, DEA approved funding for a second project. The projects were accompanied by CCOP workshops held

at VPI, and "On-the-Job-Training" (OJT) programmes at GEUS for VPI geo-scientists. The implementation of these initial projects revealed the need for enhancement of the research skills of VPI geo-scientists, and support for long-term institutional development was obtained from ENRECA-programme at Danida in 2000.

The successful co-operation since 1995 has focussed on research and institutional capacity building and has included geo-scientific projects focussed toward assessment of the hydrocarbon potential of selected sedimentary basins in Vietnam. The aim has been strengthening of research capacity in Vietnam within the fields of basin analysis and modelling by offering "on-the-job-training" at GEUS in Copenhagen, technology transfer, in-house training at VPI, courses taught at the three universities, supervision of MSc. and PhD. students, preparation of technical reports and recommendations, and dissemination of research results at scientific conferences and in a large number of international publications.

Over the years, VPI, GEUS and Petrovietnam have provided considerable in-kind contributions and additional funding to further support the implementation of this comprehensive list of activities.

VPI and GEUS, considering the future challenges in E&P of oil and gas in Vietnam and taking advantage of the vast knowledge and experiences accumulated within the joint ENRECA Research Team, will soon sign an MOU (November 2014), that will establish the framework for continuing their research co-operation in the years to come. Thus, VPI and GEUS will be able to provide jointly reliable and "demand-driven" research of high standards to both the public authorities and the industry in Vietnam and abroad.

2. Scientific results

The two first geo-scientific projects were aimed at analysis of the hydrocarbon potential of the Song Hong basin (Fig.1). Seismic interpretation, field work and evaluation of results from the few exploration wells drilled in the basin were carried out [1, 2, 6, 7, 8, 19]. Seismic facies analyses, biomarker analyses of oil samples and investigations of thermally immature potential source rocks from onshore localities, including the Dong Ho and other outcrops, where oil-prone Oligocene lacustrine mudstones and thin coals are exposed, led to the identification of areas for future exploration in the Song Hong basin [3, 22, 25, 28].

The following project was focussed toward assessment of the hydrocarbon potential of the Phu Khanh basin, which at that time was almost un-explored [18]. The available seismic data was carefully interpreted and tied to well-sections north and south of the basin. The development of the basin was analysed and a number of possible play types were identified [11, 12, 15]. Oil seeps occurring at the basin margin have been reported from the Thi Nai lagoon area, but their nature remained controversial [31]. The area was thus visited and a number of oil samples were collected and analysed. The results show the presence of biodegraded petroleum, with biological markers pointing to a marly source rock with some terrestrial input and Cenozoic lacustrine oil similar to those from the Song Hong basin [4]. Available oil samples from neighbouring basins were also analysed for comparison and discussion on the character of the source rocks [5, 26].

The next period was focussed toward the Malay and Phu Quoc basins. Significant results regarding

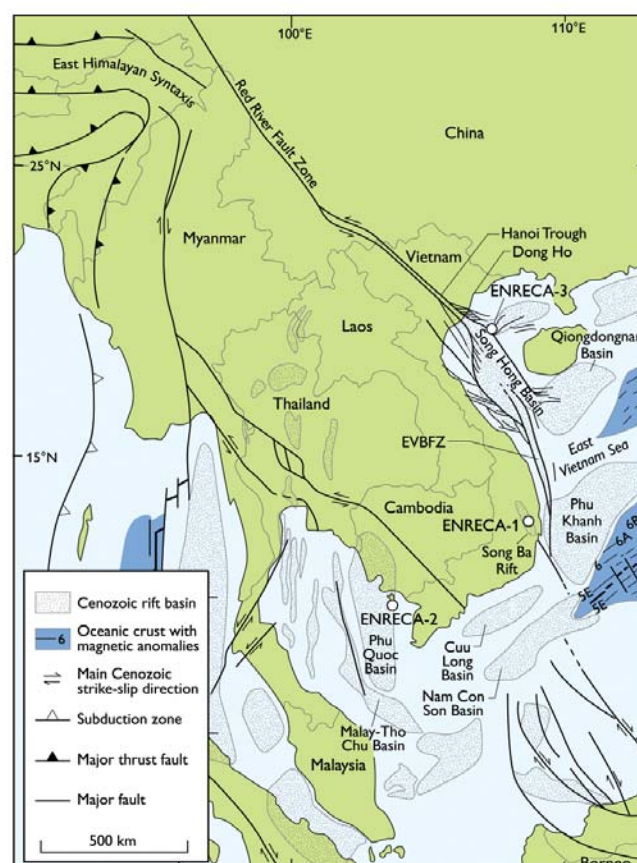


Fig.1. Tectonic framework of Southeast Asia. Notice the Vietnamese offshore basins, the Song Hong, Phu Khanh, Cuu Long, Nam Con Son and Phu Quoc basins. The position of the three stratigraphic core wells ENRECA-1, -2 and -3 are indicated in the Song Ba rift and on the islands of Phu Quoc and Bach Long Vi. The Dong Ho locality in North Vietnam is marked

the understanding of the potential of the Vietnamese part of the Malay basin were obtained by applying seismic mapping, basin modelling and the utilisation of knowledge on the Cenozoic source rock obtained from the previous studies [13, 27]. Further, the structural development of the Phu Quoc basin was analysed [10, 14].

The most recent research studies have been focussed toward a revisit to the Song Hong basin with a focus toward the north-eastern parts. The previous findings of the ENRECA research team and a number of new encouraging well results with significant oil shows have generated renewed interest in the Song Hong basin, and it was obvious that existing exploration models could be strengthened by better data on the distribution and generation potential of the source rocks. It was thus decided to carry out a comprehensive seismic mapping campaign and to drill the Bach Long Vi island. The results were presented at VPI's 35 year's anniversary and are now prepared for publication [16, 23].

2.1. ENRECA-1

The presence of lacustrine source rocks in small grabens in the offshore basins as indicated by seismic data and biomarker analyses of oil shows and seeps [3, 4, 22, 25, 28] fostered the idea of investigating the fill of the Song Ba rift in central Vietnam. The rift seems to constitute the onshore continuation of the complex Tuy Hoa fault-zone marking the southern boundary of the Phu Khanh basin (Fig.1). The scientific approach was an attempt to develop a model of small, narrow continental rifts as a supplement to the well-established models for large rift-lake systems of Sladen (1995) and Lambiasi (1990). Thus, after a reconnaissance fieldtrip followed by dedicated field work on outcrops exposing coarse-grained sandstones and conglomerates interbedded with lacustrine mudstones and scattered coal beds, it was decided to drill a core well to investigate the deeper part of the graben fill. The ENRECA-1 core well was placed in the Krong Pa graben, one of several depressions within the Song Ba rift, and the 494.5m deep well was TD-ed in granite and provided excellent cores. The core well encountered 478m of sediments beginning with thin fluvial sandstones overlying the granite. The sandstones are overlain by lacustrine mudstones interbedded with thin sandstones, whereas fluvial sandstones dominate the upper part of the core. The lacustrine mudstones contain organic matter, commonly exceeding 5wt.% and occasionally reaching up to 8.3wt.%, and many samples have a hydrogen index (HI)

of more than 300mg HC/g TOC, occasionally up to 800mg HC/g TOC (Fig.2). The organic matter is mainly composed of fluorescing amorphous organic matter, alginite, and liptodetrinite, corresponding to type I kerogen and is an excellent source for oil. The cores thus show oil-prone source rocks of good to excellent quality attaining a cumulative thickness of approx. 50m. The results suggest formation of oil-prone mudstones primarily during rift climax when sedimentation rate was outpaced by formation of new accommodation space.

The cores in combination with information from other core wells in the area and the investigated outcrops led to the establishment of a local model describing the development of the graben fill (Fig.3 [21]). This local Krong Pa model has been combined with the general model of Lambiasi (1990), a conceptual model with large impact on exploration strategy has been proposed (Fig.4). The conceptual model proposed that if small grabens located on a string within a faulted zone is connected by a major trunk river system as the Song Ba ancestor river, the upstream grabens may function as sediment sinks that catch the coarse clastic river bed loads, whereas the lower downstream grabens may function as the locus for establishment of lakes in which prolific algae production may lead to the formation of lacustrine oil-prone source rocks. This clearly shows that even small and narrow (downstream) grabens may have a hydrocarbon potential, and this exploration model may be used in the offshore basin, where careful analyses of seismic facies may pinpoint the location of sweet spots.

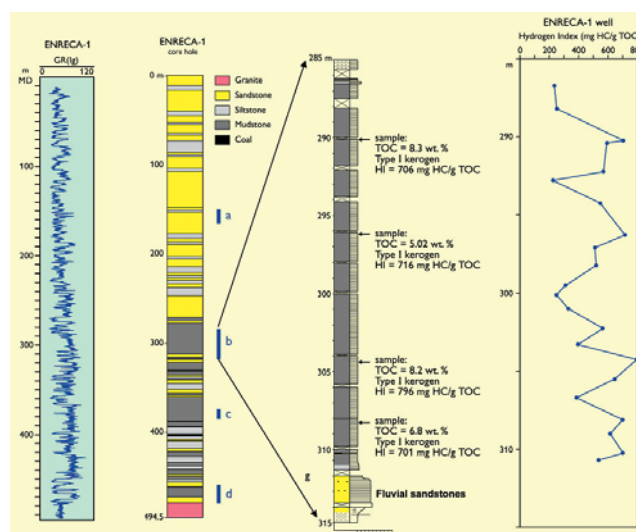


Fig.2. The ENRECA-1 core well showing a gamma-ray (left), general lithology, a selected detailed log of the upper lacustrine mudstones sequence with specific samples marked, and measured HI values shown (right). Refer to Fig.1 for location

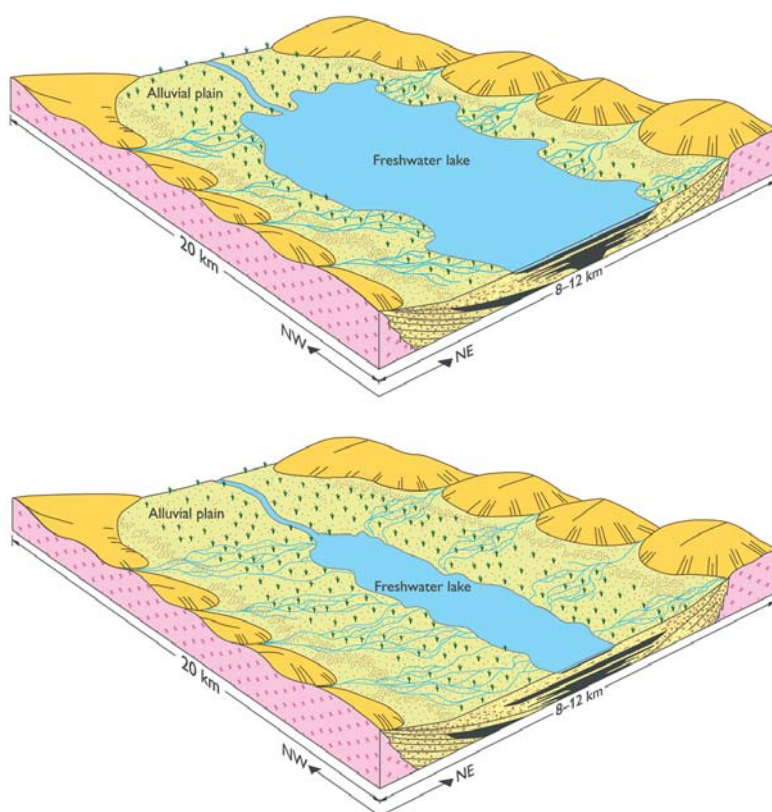


Fig.3. A schematic model showing high lake level in a small graben during rift climax when formation of new accommodation space exceeds deposition (left). The graben is dominated by fluvial deposition during the waning phase of subsidence (right)

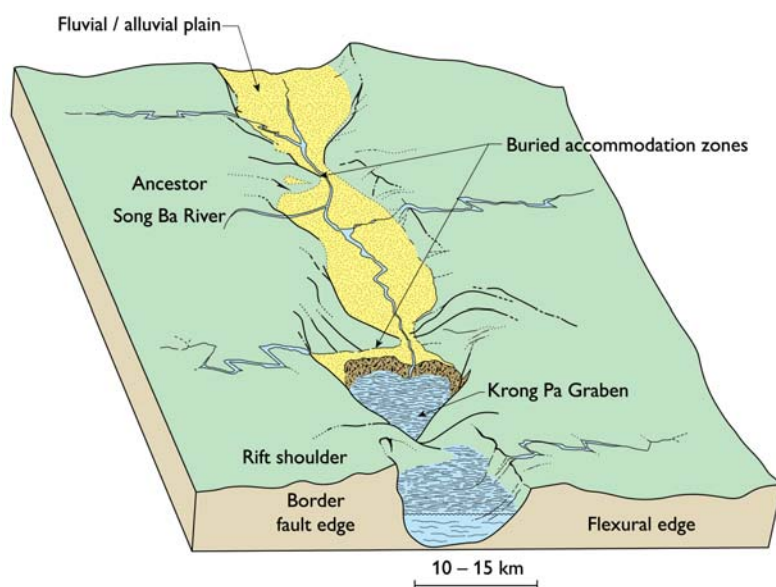


Fig.4. Block diagram showing a series of grabens located within a fault zone. The proximal upstream grabens are filled with fluvial sand and function as sediment sinks, whereas the downstream distal grabens are more prone to accumulate lacustrine mudstones, in particular during periods of rapid subsidence and formation of accommodation. Applied to the Song Ba rift system, the Krong Pa graben (and the grabens further downstream in the offshore Tuy Hoa shear zone) corresponds to the distal grabens shown occupied by prolific freshwater lakes with deposition of organic-rich mudstones. Modified from Lambiasi (1990)

2.2. ENRECA-2

The Phu Quoc basin is located in the Gulf of Thailand offshore Southwest Vietnam and continues onshore Southern Cambodia (Fig.1). The available offshore seismic data shows a complicated structural development, and the basin is poorly explored and its hydrocarbon potential is difficult to assess. The Phu Quoc Island forms part of the north-south trending deformation belt that continues onshore Cambodia in the Elephant mountain belt and exposes parts of the Upper Mesozoic basin fill [14]. As an attempt to contribute to better constrained assessment of the basins hydrocarbon potential, field work was carried out on the Phu Quoc island and in Cambodia. The island mainly exposes Lower Cretaceous fluvial sandstones and conglomerates. Furthermore, seismic analyses, evaluation of well-sections and analyses and modelling of source rock maturation led to identification of possible source rock kitchens and contributed to the existing exploration models of the Vietnamese part of the Malay basin [13, 14, 24].

The ENRECA-2 core-well was placed on the south-western tip of the island and it provided 504 high quality cores interbedded with variegated mudstones and siltstones. The sandstones show weakly upward-fining channel successions with sharp erosive bases marked by pebbles of variable lithology overlain by thick cross-bedded, coarse- to medium-grained sandstones, which show an upward decreasing bed thickness (Figs.5 & 6). The sandstones contain scattered coalified wood fragments. The interbedded greenish, reddish and brownish mudstones and siltstones typically form few metres thick successions showing parallel lamination and small ripples. Rootlets are common and fragments of leaves and wood occur in places, but coal beds have not been observed. Large tree trunks, forming the so-called jet coal are reported to be abundant at a few stratigraphic levels on the island probably recording humid periods with a high groundwater table. Marine shoreface sandstones with abundant trace fossils occur at few stratigraphic levels in the cores and in

outcrops (Fig.6); the shoreface sandstones are associated with lagoonal mudstones and siltstones containing few marine dinoflagellates in the well [29].

The sandstones are mainly coarse- and medium-grained, in places fine-grained, and are mostly well cemented mainly with poor visible porosity. Petrographic analyses show they may be classified as sublitharenite, litharenite and feldspathic litharenite containing mainly quartz, minor feldspar, mica and common rock fragments, in particular of volcanic and metamorphic origin. Well log evaluation and macro- and microscopic evidence indicate intervals with 10 - 15% porosity, and up to 20% in a few places. Screening

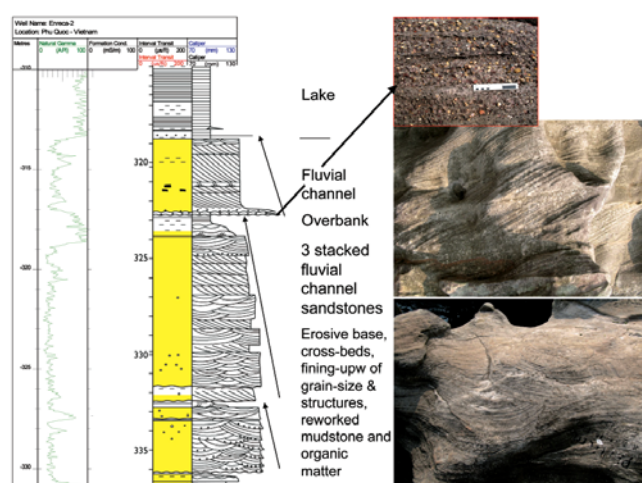


Fig.5. Selected part of the ENRECA-2 core well showing well logs and sedimentological core log with interpretations. The cored succession consists of fluvial cross-bedded, coarse-grained, sandstones and lacustrine mudstones. Outcrop examples of fluvial cross-beds and parallel-stratified pebbly sandstones are shown (right)

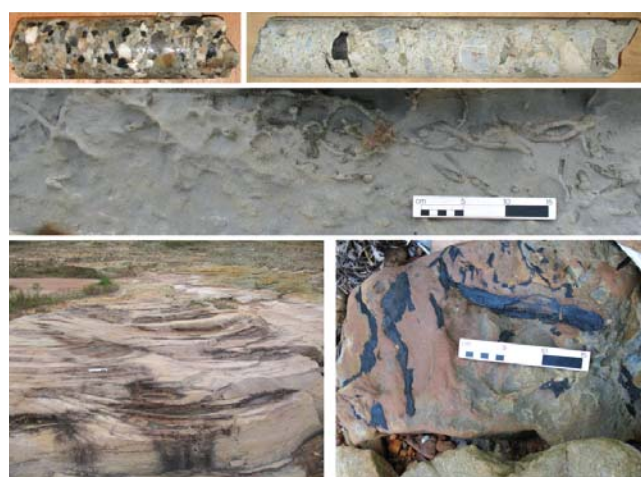


Fig.6. Selected photos of cores and outcrops. The two core pieces show polymict conglomerates indicating a complex source area (upper). An example of bioturbated, shallow marine sandstone exposed on the southeast coast (middle). Trough cross-bedded medium-grained sandstones and coalified wood fragments in fluvial sandstones (lower)

analyses of core and outcrop mudstones samples indicate a very low hydrocarbon generation potential.

2.3. ENRECA-3

The Bach Long Vi island constituting the uppermost part of a Neogene inversion structure situated at the intersection of the Song Hong and Bei Bu Wan basins provides a unique geological window into the Paleogene syn-rift fill of the basins (Fig.7). Oil-prone lacustrine source rocks have been documented from the island and the sea bottom around it [25], but exploration wells located nearby such as the 107Pa-1x that drilled a thick syn-rift succession did not encounter hydrocarbon shows nor source rocks [3]. This disappointing result halted exploration in the area for some time, and the need for investigating this enigma increased. The ENRECA team thus suggested Petrovietnam to drill a fully cored well on the island to investigate the inverted syn-rift succession and the thickness and composition of the potential source rocks. It was decided to place the well in the south-eastern corner of the island to supplement the exposed stratigraphy. The well was drilled in spring 2012 and has provided excellent cores with a very high recovery (Fig.8).

The cores have been logged sedimentologically and on the basis of the detailed core log a large number of samples for source rock screening, sandstone petrography, clay mineralogy, por-perm measurements and biostratigraphy were sampled. Although a detailed and integrated interpretation of the many results remained to be concluded by the ENRECA research team, several

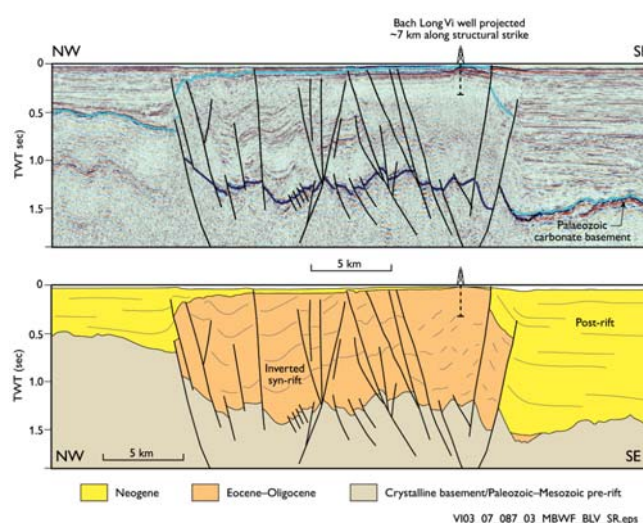


Fig.7. Interpreted seismic section and geo-section from the Bach Long Vi graben illustrating the inverted Paleogene syn-rift section. The Bach Long Vi island constitutes the top part of the inversion structure and offers a geological window into the syn-rift section

important conclusions can be drawn. The cored section constitutes a continuous succession without indications of significant unconformities or stratigraphic breaks. No significant faults are cutting the core succession. The absence of marine macro- and micro fossils, the abundance of freshwater algae, spores and pollen, the absence of fluvial and shallow water deposits and the presence of laminated mudstones with interbedded

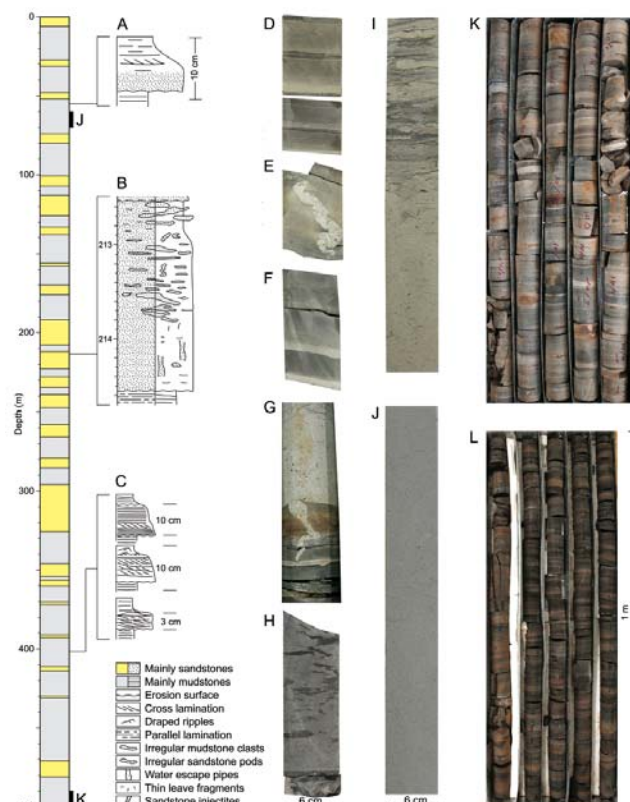


Fig.8. Simplified lithological log of the 500m deep ENRECA-3 well (left) showing ca. 163m of sandstone-dominated intervals (yellow) interbedded with intervals dominated by mudstones (grey). Detailed logs of thin-bedded turbidites Bouma T_{abcde} (A) and T_{cde} (C) occurring interbedded with the mudstone source rocks are shown to illustrate the complicated nature of the succession. (B) Sedimentological log of thick density-current deposits (hybrid bed) with water-escape structures, floating intraformational rip-up clasts of mudstones and pods of sandstones. (D) and (F) show core pieces of thin-bedded fine-grained turbidites; (E) Sandstone injected into soft mud and later compacted. (G) Grey mudstones with thin sandstone layers and brownish concretion and injected sand at the base of an overlying density-current sandstone. (H) Muddy sandstone debrite with poor por-perm; (I) Sandstone dominated hybrid bed with land-derived organic debris; (J) Thick sandstone turbidite with delicate leave fragments and fair por-perm. (K) Light grey mudstones alternating with thin fine-grained sandstones and brownish cemented layers and concretions. The mudstones are highly oil-prone. (L) Dark grey to black, highly oil-prone mudstones alternating with light grey to greyish/brownish mudstones with a lower and varying generation potential. Modified from Petersen et al. 2014

sandstones indicate that the depositional environment was deep lacustrine. The age has been determined to Late Oligocene on the basis of poor biostratigraphic evidence as age-diagnostic fossils are poor [9]. Deposition of organic-rich pelagic and hemi-pelagic mud on a dysoxic lake bottom dominated. Occasionally, due to collapse of the more shallow parts of the lake and lacustrine deltas coarser-grained sediment was brought by turbidity currents and other sediment gravity flows to the deep part of the lake, where sand, silt and mud was deposited on the soft lake bottom often causing spectacular soft sediment deformation structures (Fig.8). The thicker turbidite beds are mostly medium-grained, fairly clean sandstones with fair porosities, whereas the muddy debrite beds have poor reservoir properties. Based on the source rock screening data in combination with the sedimentological corelog, the cumulative thickness of the excellent oil-prone source

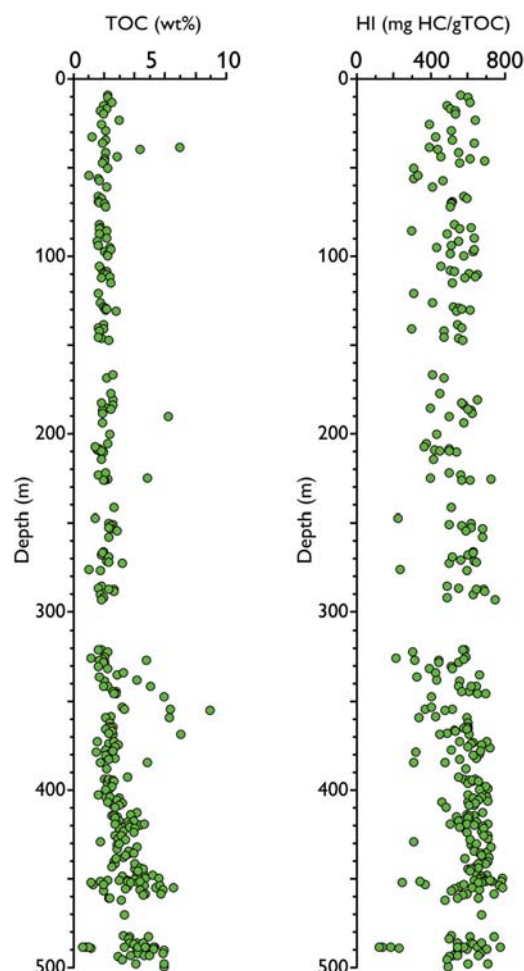


Fig.9. Source rock screening data showing the high TOC and HI values throughout the cored section. Note that the high values most likely continue below the cored section; in addition high values are found in the outcrops on the island that represents a higher stratigraphic level above the top of the cored section. Modified from Petersen et al. 2014

rocks is estimated to approx. 233m (Fig.9). The cumulative thickness of beds without an oil-generating potential or a poor potential, i.e. the thicker sandstones, the numerous thin sandy and silty turbidites and the many concretionary beds amounts to approx. 163m. The cumulative thickness of fine- to medium-grained sandstones thicker than 0.2m have a cumulative thickness of approx. 55m and these may serve as conduits or reservoirs for generated hydrocarbons. In addition to the "thick-bedded" sandstones, the numerous thin-bedded (cm-scale) very fine- to fine-grained turbidite sandstones, which are intimately interbedded with the source rock mudstones, may together with the sandstone injectites such as vertical dykes form a very effective drainage system for generated hydrocarbons.

The core well was therefore a great success demonstrating the presence of thick world-class source rocks interbedded with carrier beds. Furthermore, the cored succession shows no indications of a declining source rock quality towards the base of the cores succession and we also know from the outcrops that several tens of metres of source bearing strata occur above the core section (Fig.9). Thus the above mentioned cumulative thicknesses of the source rocks are minimum figures.

3. Future challenges

The conditions for the continued research co-operation between GEUS and VPI are changed now that the financial support from ENRECA/Danida is coming to a definitive end. This long-term co-operation has been very successful and has overcome a number of challenges and obstacles. The scientific success is confirmed by the great number of co-authored international papers in peer reviewed journals and the many oral and poster presentations at conferences that have received overwhelming recognition and acknowledgement by the international research community and the industry. With the upcoming research co-operation agreement (MOU) between VPI and GEUS, the organisational framework for new initiatives and projects will be defined. The ENRECA research team has through the years identified a number of tasks and projects, the implementation of which would strongly strengthen the existing understanding of the geological development of the Vietnamese basins and their hydrocarbon potential.

One of the most obvious initiatives to be taken is a thorough study of the implications of the very positive ENRECA-3 findings. This well has provided invaluable

new geoscientific information for the study area, but it has also raised a number of significant research questions of mandatory importance for understanding the oil potential of the North-eastern Song Hong basin: which geological factors - such as structural development, climatic conditions, drainage patterns, bed rock geology etc. - governed the formation and distribution of the syn-rift lacustrine source rocks? If the determining influence of these factors can be fully understood, the present day occurrence of mature source rock pods (i.e. hydrocarbon kitchens) can be mapped out, and an effective exploration strategy for the area can be lined out. Thus, as a result of these considerations, the ENRECA research team has proposed the initiation of a multi-disciplinary and integrated study that, among others, must include tectonic restoration, sequence stratigraphic analyses, detailed sedimentological investigations of the mudstones, studies of the activation energies of the organic components in the source rocks. The integration of the findings of these studies will contribute greatly to the establishment of a new reliable predictive exploration model for the selected study area.

Another obvious research task is to reduce the exploration risk by focussing toward predictions of reservoir quality. Different rock types exposed to weathering processes provide great variability in the resulting sediments depending on factors such as climate, transportation and depositional environment. Thus source to sink studies could be significant contributions to exploration strategies if the studies are focussed toward the prediction of reservoir composition and quality in the offshore basins by investigating the timing and amount of uplift of the Vietnamese mainland, the timing of exposure to weathering of the various bed rock units, and mapping of paleo-drainage patterns, sediment transportation routes and the significant sediment entry points to the basins.

In addition to these research themes a number of focussed studies need to be carried out to reduce exploration risks and expenditures, and the ENRECA research team is prepared for these research challenges.

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PETROGRAPHIC CHARACTERISTICS AND RESERVOIR QUALITY OF SANDSTONE RESERVOIRS FROM ENRECA-3 WELL IN BACH LONG VI ISLAND

Bui Thi Ngoc Phuong
Vietnam Petroleum Institute
Email: phuongbntn@vpi.pvn.vn

Summary

This paper presents the relation of petrographic characteristics and diagenetic process to the reservoir quality of sandstone units in the Enreca-3 well. The results of petrographic study show that almost all studied sandstones are fine- to medium-grained ones. All studied sandstones are quite clean and classified as arkose sandstone. The detrital grains of studied sandstones are mostly angular, subangular to subrounded in grain shape and mostly poor to moderate sorting. Arkose sandstones are composed of mostly quartz and feldspar with much smaller amount of rock fragments such as granite, volcanic, quartzite, schist, and sandstone. The sediments were derived mostly from continental block provenance. The sandstones were in the early diagenetic stage. The petrographic study also reveals that the visible porosity of studied sandstones has been strongly damaged by cementation, whereas the mechanical compaction has not significantly affected the visible porosity of these reservoir sandstones. The visible porosity of studied sandstones is fairly good with mostly well preserved intergranular pores (7.6 - 19.4%, average ~15%) and minor micropores within clay patches (~1.0 - 2.0%), and further enhanced with secondary pores (1.4 - 1.8%) due to the dissolution of uncertain grains such as feldspar and lithic fragment.

Key words: Origin, diagenetic process, reservoir quality, sandstone, Enreca-3.

1. Introduction

The ENRECA-3 well is located in Bach Long Vi island in the northeast of Song Hong basin. This is a fully cored well with approximately 500m in the interval from 0m to 500m. According to legacy data, the sediments in this studied interval belong to late Oligocene and were deposited within the deep water lacustrine [1]. The reservoir quality of sandstones is often controlled by diagenetic processes (i.e. cementation, compaction, dissolution and mineral conversion) and by the rock texture such as grain size, grain shape and grain sorting. After sand has been deposited and buried, sediments begin to undergo diagenetic processes, which turn the unconsolidated materials into a sedimentary rock. To predict the reservoir quality of sandstone reservoir rocks, we need to measure the effects of diagenesis on porosity and permeability. This requires a quantitative understanding of what cements occur in the reservoir rock and how they are distributed.

This study programme, with a total of twenty core samples in the interval from 101.25m to 371.93m and from 18.30m to 499.68m, was carried out using thin section analysis and XRD analysis for clay fraction, respectively. Thin section analysis helps to estimate the rock-forming minerals, rock texture, rock name, post-depositional alteration as well as the relation of other characteristics of the rock to the reservoir quality. The determination of mineral composition and visible porosity has been

performed by the modal analysis of 500 counting points in each thin section after the method of L.Van der Plas [4]; Soloman and Green [5]. The sandstone is classified using R.L.Folk's classification [7]. The grain size distribution of sandstones was measured by long diameter of 100 grains per thin section. The textural terminology such as mean grain-sized (Mz), grain sorting ($\delta 1$), grain size distribution (SK1) and the peakedness of grain size distribution (Kg) is based on the classification of R.L.Folk and W.C.Ward [6]; F.J.Pettijohn [3]. The classification of the forming provenance is based on plate tectonic and sandstone composition of Pettijohn, 1973 and Dickinson [10]. Assessment of the relationship of the compaction process and cementation to damages of porosity in sandstones is after David W.Houseknecht [2]. The clay fraction analysis determines the volume percentage of each individual clay mineral of sandstones and helps to define the burial diagenetic evolution of the rocks.

2. Results and discussion

Petrographic analysis shows that all studied samples in the interval between 101.25 - 371.93m are arkose sandstones according to R.L.Folk's classification (Fig.1). The classification of the forming provenance of the rock is displayed in Fig.2, which reveals that arkose sandstones were mostly originated from continental block provenance.

The texture and the detailed composition of the reservoir sandstones are shown in Table 1 and the

Table 1. The petrographic data of sandstones from Enreca - 3 well

TEXTURE		MINERAL COMPOSITION (%)																Visible porosity																			
		MINERAL COMPOSITION (%)																																			
		Grain size (mm)				Framework grains				Accessory minerals				Matrix/ Pseudo-matrix					Cement and authigenic minerals																		
Max	Min	Mode grain sire	Mean grain size (Mz)	Sorting(δ1)	Sorting class	Roundness	Grain contacts	Quartz	K-Feldspar	Plagioclase	Mica	Granitic	Volcanic	Schist	Quartzite	Sandstone	Apatite	Zircon	Tourmaline	Epidote	Sphene	Clay minerals	Volcanic ash	Organic matter	Kaolinite (illitised)	Chlorite	Muscovite/sericite/other clays	Calcite	Dolomite	Siderite	Quartz	Albite	Opaque mineral				
101.25	Arkose	1.50	0.10	0.25-0.5	0.40	1.01	P	A-SA/5R	P-L	Grain contacts	Quartz	27.2	20.8	1.6	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0		
113.57	Arkose	0.80	0.03	0.125-0.25	0.14	0.53	M-G	A-SA/5R	P-L	Roundness	Quartz	30.0	18.0	3.0	4.0	Tr	1.2	1.0	0.8	Tr	Tr	Tr	2.6														
121.87	Arkose	1.50	0.05	0.25-0.5	0.29	1.12	P	A-SA/5R	P-L	Grain contacts	Quartz	30.2	20.6	3.8	1.8	3.0																					
204.74	Arkose	2.20	0.10	0.25-0.5	0.47	1.04	P	A-SA/5R	P-L	Grain contacts	Quartz	29.8	19.4	3.2	2.8	3.8	0.4	2.0	1.0	Tr	Tr	Tr	0.2	Tr													
230.02	Arkose	0.80	0.05	0.25-0.5	0.27	1.00	P	A-SA/5R	P-L	Grain contacts	Quartz	29.6	21.0	4.2	3.0	4.2		0.6	1.0	Tr	Tr																
262.40	Arkose	1.20	0.05	0.25-0.5	0.28	0.96	M	A-SA/5R	P-L	Grain contacts	Quartz	30.4	19.8	5.0	1.0	4.0	1.0	1.0		Tr	Tr	Tr															
281.39	Arkose	0.40	0.05	0.125-0.25	0.19	0.57	M-G	SA-SR-R	P-L	Grain contacts	Quartz	31.0	18.2	5.2	3.0	2.0	0.4	Tr	1.0	Tr	Tr	Tr															
297.60	Arkose	0.60	0.05	0.25-0.5	0.33	0.79	M	SA-SR-R	P-L	Grain contacts	Quartz	32.8	20.0	4.8	1.2	2.8		1.0		Tr	Tr	0.2	Tr														
300.68	Arkose	1.20	0.05	0.25-0.5	0.25	0.71	M	SA-SR-R	P-L/C	Grain contacts	Quartz	31.8	20.8	4.0	1.4	2.0		1.0		Tr	Tr	Tr															
371.93	Arkose	0.50	0.05	0.125-0.25	0.17	1.00	P	A-SA/5R	P-L/C	Grain contacts	Quartz	33.0	21.0	3.8	3.0	1.0		1.0		Tr	Tr	Tr															

Notes: M-G: Moderate - good
M: Moderate
P: Poor
A: Angular
SA: Subangular
SR: Subround
R: Round
P: Point
L: Long
C: Concavo-convex
Tr = Trace
/: With some

Table 2. The statistical parameters of grain size analysis for sandstones from Enreca-3 well

Depth (m)	101.25	113.57	121.87	204.74	230.02	262.40	281.39	297.60	300.68	371.93
Median diameter - ϕ scale (Md = ϕ 50)	1.29	2.84	1.59	0.95	1.70	1.72	2.37	1.55	1.90	2.55
Median diameter- mm scale (Md = P50)	0.41	0.14	0.33	0.52	0.31	0.30	0.19	0.34	0.27	0.17
Mode diameter- ϕ scale (Mo- ϕ)	1.04	2.65	1.63	0.83	1.69	1.63	2.20	1.36	1.77	2.33
Mode diameter-mm scale (Mo-mm)	0.49	0.16	0.32	0.56	0.31	0.32	0.22	0.39	0.29	0.20
Mean diameter - ϕ scale (Mz- ϕ)	1.32	2.86	1.80	1.08	1.88	1.84	2.42	1.61	1.99	2.57
Mean diameter - mm scale (Mz-mm)	0.40	0.14	0.29	0.47	0.27	0.28	0.19	0.33	0.25	0.17
Standard deviation (σ_1)	1.01	0.53	1.12	1.04	1.00	0.96	0.57	0.79	0.71	1.00
Skewness (SK1)	-0.09	-0.13	0.10	-0.02	0.06	-0.02	-0.10	-0.06	-0.04	-0.07
Kurtosis (KG)	1.42	1.19	1.04	1.16	0.88	1.08	1.11	1.04	1.13	0.97

Note:

Median diameter: The size is most readily determined from the 50% line of the cumulative distribution curve

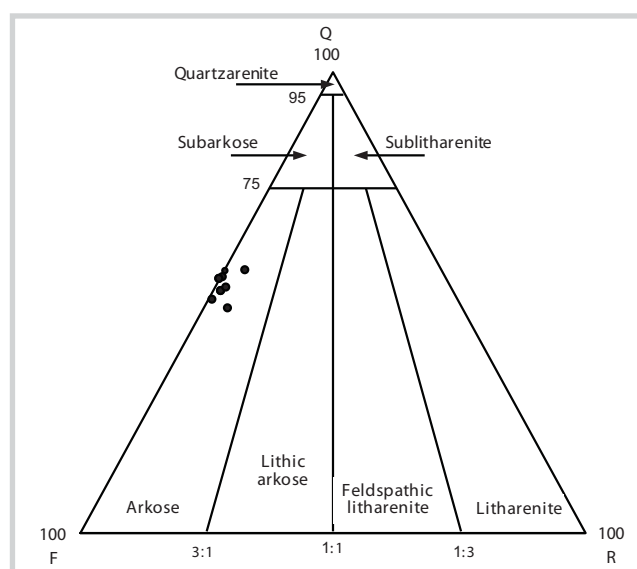
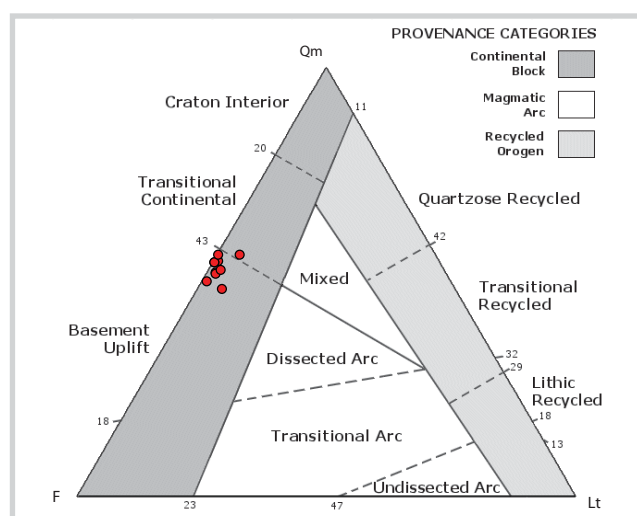
Mode diameter: The mode size is the commonest grain size in a distribution

Mean diameter: The best measure of average grain size.

summary of petrographic component is shown in Fig.3. Table 2 shows the detailed result of grain size analysis. These results indicate the arkose sandstones are mostly fine-grained to medium-grained sandstones with several of fining-upward cycles, in which the mean grain size (Mz) ranges from 0.14mm to 0.47mm. The detrital grains are common angular, subangular to subrounded in grain shape and typically poor to moderately good sorting, in which the standard deviation value (σ_1) ranging from 0.53 to 1.12. The compaction is commonly weak to moderate with mostly point to point and long type in grain contacts (Fig.4 & 5). The compaction tends to increase downward from the depth of 300.68m with concavo-convex grain contact type.

Figs.3, 4 and 5 show that the arkose sandstones are predominantly made up of quartz (average ~31%), k-feldspar (average ~20%) with subordinate amount of plagioclase (average ~4%) and mica (average ~2%). Rock fragments are present in a considerable amount as mainly granite (average ~3%) with other minor lithics as volcanic (scattered ~1%), schist (scattered ~1%) and quartzite (average ~1%). Studied sandstones in this interval are quite clean without detrital matrix materials or negligible (scattered ~2 - 4%). The detrital matrix materials are predominately made up of clay minerals, intermixing with volcanic ash and organic matters. The detrital matrix materials partly filled up the intergranular pores.

Figs.4 and 5 show poorly sorted medium-grained arkose sandstones. Detrital grains are mainly angular, subangular to subrounded and typically weakly compacted with point to point and long contacts. Detrital grains contain mostly quartz, feldspar, mica and rock fragments. Feldspar grains are present in a considerable amount as


Fig.1. The classification of sandstone with less than 15% fine-grained matrix. After R.L.Folk's classification, 1974

Fig.2. The relation between tectonic settings and sedimentary materials of reservoir sandstones from Enreca-3 well. After William R. Dickinson, 1979

k-feldspar (stained in yellow) and minor plagioclase, some of them have undergone partial dissolution and been locally replaced by sericite, muscovite and clay minerals. Minor detrital mica flakes are present as muscovite (Mus) and biotite, some of them have slightly been replaced by chlorite (Ch) minerals. Rock fragments are present as granite, schist, quartzite and sandstone. The sandstones are quite clean with minor detrital matrix materials. Authigenic minerals are present with moderate amount

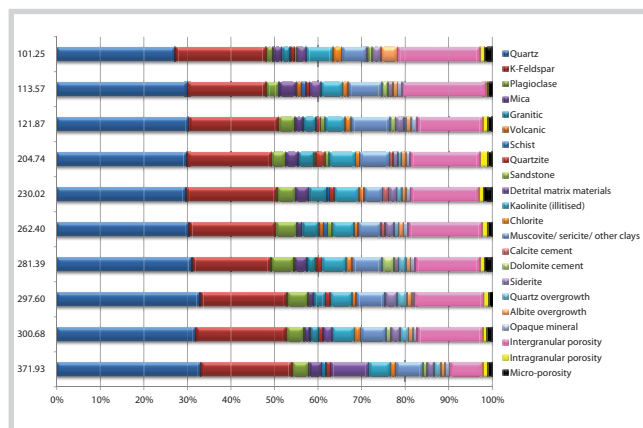


Fig.3. The summary of petrographic data of sandstones from Enreca-3 well

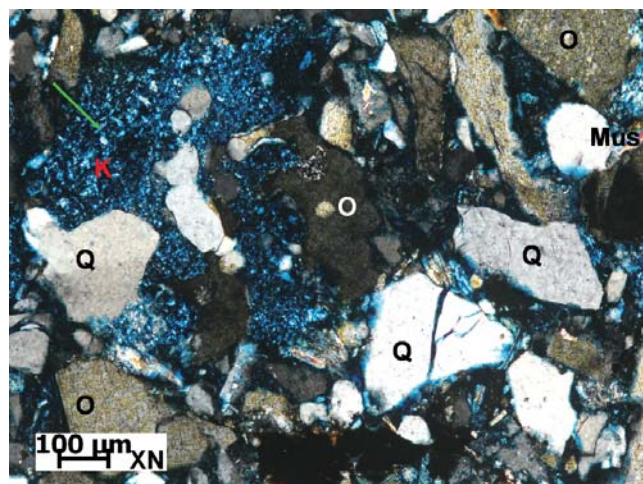


Fig.4. 121.87m depth from Enreca-3 well

as pore-filling kaolinite (K), siderite, chlorite, calcite, dolomite, albite, sericite-muscovite-other clay minerals and opaque minerals. These authigenic minerals are not only replacing feldspar grains but also partly filling up pore spaces. Locally, kaolinite clays have been replaced by fibrous illite.

Cement and authigenic minerals are present in almost all sandstones in a considerable amount with mostly diagenetic clay minerals as kaolinite (average ~5.5%), chlorite (average ~1.3%), muscovite/sericite (average ~6.5%) and minor calcite (scattered from trace - 1.4%), dolomite (scattered from trace - 2.8%), siderite (average ~2.0%), quartz overgrowths (average ~1.4%), albite (average ~1.3%) and opaque minerals (average ~1.0%). Diagenetic minerals not only partly replaced feldspar grains but also filled up the intergranular pores and secondary pores.

These arkose sandstones have strongly been cemented with authigenic minerals such as diagenetic clay minerals, quartz overgrowths, opaque minerals, and carbonate minerals. Although the mineralogical maturity and textural maturity of these arkose sandstones are not

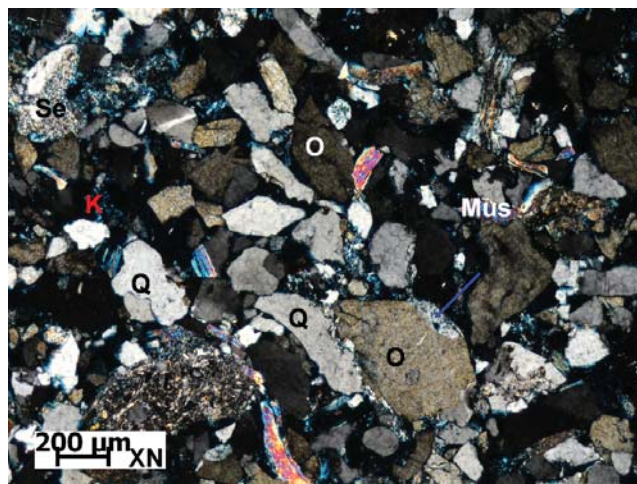


Fig.5. 230.02m depth from Enreca-3 well

Table 3. The XRD analytical result for clay fraction of samples from Enreca-3 well

No	Depth (m)	Kaolinite	Chlorite	Illite	Smectite	Illite-smectite
1	101.25	17.4	5.7	45.7	29.0	2.1
2	113.57	31.0	5.0	54.7	4.5	4.9
3	121.87	20.2	7.9	54.1	12.4	5.4
4	204.74	20.7	5.8	47.6	21.8	4.1
5	230.02	22.4	8.1	52.9	6.5	10.1
6	262.40	20.6	7.3	59.9	6.4	5.8
7	281.39	20.5	8.1	61.2	5.8	4.5
8	297.60	20.1	6.3	42.9	8.7	22.1
9	300.68	18.0	8.2	50.5	4.5	18.8
10	371.93	17.4	8.4	63.1	5.4	5.6

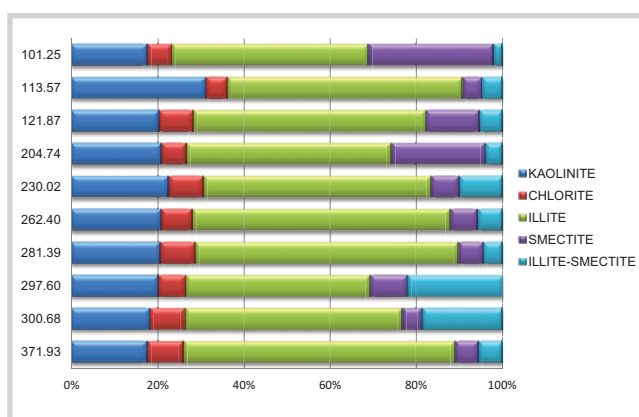


Fig.6. The summary of clay fraction data of samples from Enreca-3 well

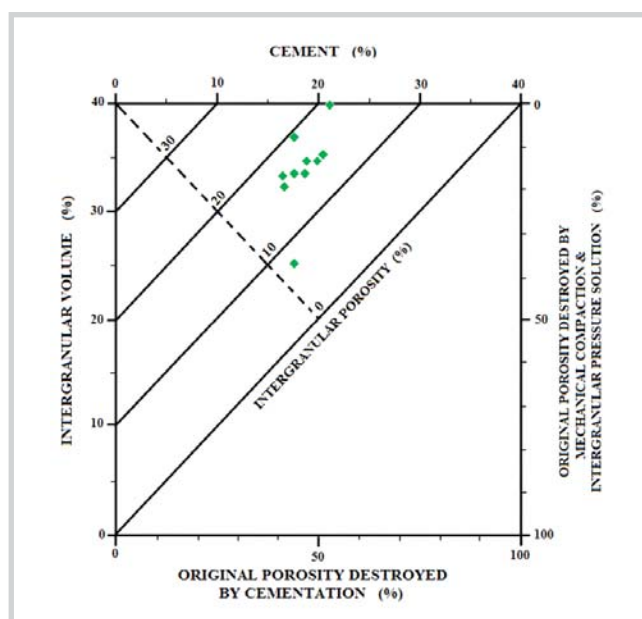


Fig.7. The original porosity destruction of reservoir sandstones from Enreca - 3 well due to mechanical compaction and cementation [10]

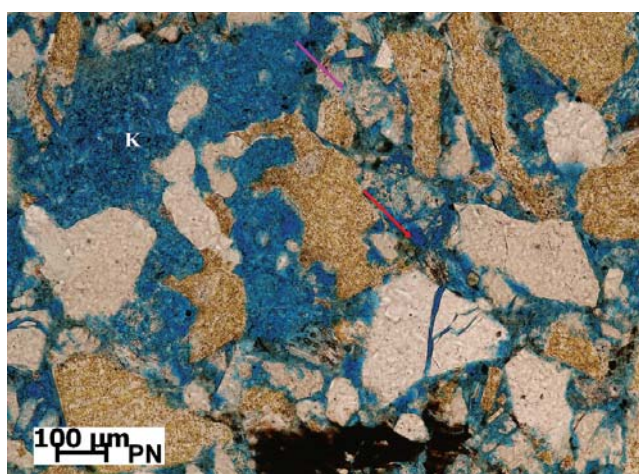


Fig.8. Depth 121.87m

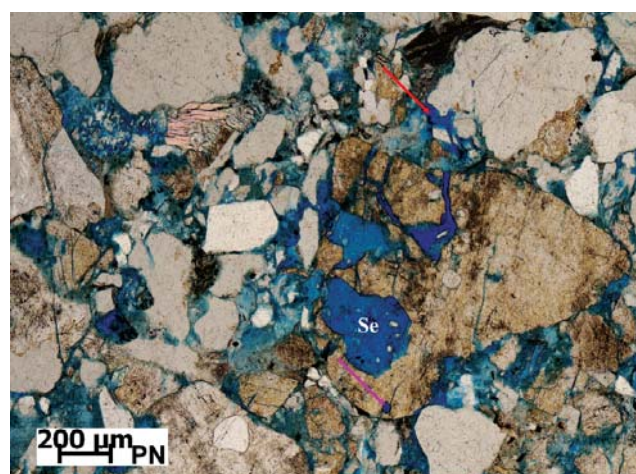


Fig.9. Depth 204.74m

The figures indicate reservoir sandstones have very good reservoir quality. High levels of visible porosity are present as mostly preserved intergranular pores (red arrows) with minor micropores within kaolinite patches (K) and significantly enhanced by secondary macropores (Se, pink arrows) due to the dissolution of unstable grains as feldspar grains.

high, the rocks have undergone a slightly mechanical compaction. Those help to preserve the pore size and pore throat size.

The XRD analytical result for clay fraction of the rocks in the studied interval from 18.30m to 499.68m is displayed in Table 3 and the data summary is shown in Fig.4. The result reveals that clay minerals are predominantly made up of illite (average ~53.0%), followed by kaolinite (average ~21.0%), smectite (average ~10.0%), chlorite (average ~7.0%) and mixed-layer clay minerals of illite-smectite (average ~8.0%). The clay analytical result indicates that all clay minerals have intermittently increased and decreased; this suggests that clay minerals in the studied interval were not significantly affected by high thermal condition or by the burial depth; whereas the clay minerals of rocks in studied interval have been formed by chemical weathering of minerals containing Al and Si. The rocks have been deposited in stable conditions and are probably in an early diagenetic stage. In this stage, the transformation of clay minerals is significantly controlled by the depositional environment and the source rock.

In general, with progressive increase in burial depth smectite has been converted into illite or chlorite [9]. The irregular increasing and decreasing of smectite in this interval indicate that the source of sediments was derived from volcanic ash. Clay mineral assemblage such as kaolinite, chlorite and illite tends to increase or decrease irregularly; this may suggest that the formation of clay minerals in this studied interval did depend on source rock, modes of sediment transport and sedimentation environment. The presence of chlorite

suggests that the source rock is probably from the weathering of intermediate and basic crystalline rocks or low grade metamorphic rocks. The presence of illite and kaolinite suggests their deviation from crystalline rocks containing feldspar and mica or from pre-existing soils and sedimentary rocks. The other hypothesis is that the presence of kaolinite is probably from the subsequent leaching of the minerals from granitic and basis rocks in the hinterland. The irregular increasing and decreasing of illite may suggest that there appears intermittent transgressive trend in this studied interval.

Normally, at the depositional surface, the sandstone has roughly 40% porosity [2], which will be reduced by burial diagenesis such as compaction, intergranular pressure solution and cementation. Fig.5 reveals that roughly 50% of the original porosity of reservoir sandstones in the studied interval 101.25 - 371.93m from Enreca well has been destroyed due to cementation; whereas only ~15% of the original porosity of reservoir sandstone has been damaged due to compaction. The petrographic analysis also supports these results, as the sandstones contain a considerable amount of authigenic minerals and almost all detrital grains display point to point and long grain contacts.

Figs.8 and 9 indicate that the sandstone with high levels of visible porosity is present mostly as preserved intergranular pores (average ~16%) with minor micropores (roughly 1%) within clay patches and significantly secondarily enhanced by partial dissolution of feldspars and lithics (roughly 1.5% of secondary pores).

3. Conclusions

The analytical results of this study have indicated that:

- Reservoir sandstones from Enreca-3 are fine to medium grained arkose sandstones with low mechanical maturity and mineralogical maturity;
- The detrital framework modes of sandstones were derived from continental block provenance and sporadically from uplifted basement provenance;
- The original porosity of reservoir sandstones has been severely damaged due to cementation and furthermore by compaction;
- High levels of the visible porosity of reservoir sandstones are present mostly as preserved intergranular pores with minor micropores and secondary pores.

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CHARACTERISATION AND DISTRIBUTION OF HYDROCARBON IN SONG HONG BASIN

Nguyen Thi Dau¹, Ha Thu Huong², Le Hoai Nga², Phan Van Thang², H.P.Nytoft³, Henrik I.Petersen³, Lars H.Nielsen³

Jørgen Bojesen-Koefoed³, Ioannis Abatzis³

¹Vietnam Petroleum Association (VPA),

²Vietnam Petroleum Institute (VPI)

³Geological Survey of Denmark and Greenland (GEUS)

Email: daunt@vpi.pvn.vn

Summary

Compared to other Tertiary basins of Vietnam, the Song Hong basin is less prolific. The density of oil and gas discoveries is therefore not sufficient for detailed geochemical characterisation of the petroleum in the entire basin. However, based on the available data the authors have analysed the geochemical characteristics of hydrocarbons (HC) and source rocks in the study area and got the following results:

- There are four HC groups that could be recognised in the Song Hong basin: Hydrocarbon with mainly terrestrial sources from blocks 102 and 103 (Miocene inversion zone); Hydrocarbon with mainly lacustrine sources from blocks 106 and 107 and well B10 STB-1X (NE Song Lo differential zone and Bach Long Vi zone); Hydrocarbon with mainly terrestrial sources from block 112 (Hue Da Nang sub-basin); Hydrocarbon from blocks 118 and 119 and migrated HC from block 120 (Tri Ton horst) and HC from block 113 (central sub-trough);
- The distribution of HC and source rock samples on the diagrams demonstrates the close relationship between oil and source rock on the same structural element in the basin;
- It is possible that the migration distance of HC in the Song Hong basin is not long;
- The distribution of HC suite in the structures in the Song Hong basin is to be studied in further research.

Key words: Song Hong basin, Miocene inversion zone, NE Song Lo differential zone, Benzene-Toluene-Xylene, 4-methyl C30 Sterane

1. Introduction

The Song Hong basin covers approximately 220,000km² of surface area; in Vietnamese territory, it occupies 126,000km², 4,000km² of which belongs to the onshore Hanoi trough and the shallow marine area. The remaining area belongs to the Gulf of Bac Bo and offshore Central Vietnam. Hydrocarbon exploration activities in the Song Hong basin started in the beginning of the 60s of the last century, but mainly focused on onshore areas with the first gas discovery being the Tien Hai C gas field (TH-C) in 1975. When Vietnam declared its Renovation Policy in 1988, especially with the promulgation of the foreign investment policy, the Song Hong basin was extensively investigated and explored with the signing of twelve Production Sharing Contracts (PSC) for both onshore and offshore activities [2]. This study focuses on the offshore area.

Likewise, exploration drilling in the offshore area was mainly conducted by foreign operators. Since 1990, more than 40 exploration wells have been drilled. The shallowest well on the Qua Vai structure reached 1,050m TVD and the deepest well on the Bach Tri structure reached

4,114m TVD. The density of exploration wells is about one well/3,200km². Among the wells drilled in the area, more than 70% of them had moderate to good hydrocarbon shows and discoveries.

The Song Hong basin is a Tertiary sedimentary basin formed from a NW-SE trending pull-apart graben and its flanks are bounded by strike-slip and normal fault systems. These fault systems were initiated by the collision between the Indian and the Eurasian plates during the Eocene-Early Oligocene [8]. Left-lateral strike-slip movement in the Oligocene, right-lateral movement in the Late Miocene, and pull-apart extension are the major geodynamic elements that form the Song Hong basin. Immediately following the Middle-Late Miocene tectonic inversion, the basin continued to steadily undergo thermal subsidence until the present. The Song Hong basin is a very large basin with complicated geological features, changing from the NW to the SE and from the North to the South. The basin is made up of different structural units with different hydrocarbon potential: the Northwestern margin, the Northeastern margin, the Central area and the Eastern margin (Fig.1).

The Western margin is made up of the Hanoi trough and other blocks in the west of the Song Hong basin. The prominent geological features are complicated folding structures accompanied by tectonic inversion of the Miocene succession. There are 3 structural elements in this area: Thanh Nghe shelf, Hue Da Nang sub-basin and Da Nang shelf.

The Northeastern margin is situated in northeastern Song Lo fault as well as Bach Long Vi area. The prominent geological features are folding structures accompanied by tectonic inversion in the Oligocene. This area could be divided into 4 structural elements: the Ha Long shelf, the NE Song Lo differential zone, the Bach Long Vi zone and the West Hainan shelf.

The Central basin area extends from blocks 102-103 to block 121 with water depths ranging from 10 to 120m. In this area, the basement gently dips towards the depocentre where the thickness of Tertiary section exceeds 15,000m. Structures range from drape-over (topping the basement) in the West to mud diapirs in the basin centre. The Central basin is divided into four structural elements: the Dong Quan trough, the Miocene inversion zone, the Central sub-trough and the Quang Ngai graben.

The Eastern margin, with water depths of 100 to 800m, is structurally different from the above mentioned areas. There are three structure elements in this area: the Eastern Tri Ton trough, the Tri Ton horst and the Hoang Sa differential zone.

The area is characterised by a basement high (the Tri Ton horst), which existed since the beginning of the synrift stage, uplifted at the end of the Oligocene, and thus creating favourable conditions for the formation of carbonate platforms and reef build-ups in the Middle and Upper Miocene. To the North-East and the South-East of the Tri Ton horst are the East Tri Ton trough and the Hoang Sa differential zone.

In the offshore Song Hong basin, although no oil/gas fields have been developed, HC discoveries have been made. The type of the source organic matter (OM) and the origin of HC as well as potential drainage areas (direction/distance migration of hydrocarbons) are still open questions that require additional investigations to be resolved.

2. Source rock

The analytical data of well-samples indicate that the sediments of Middle Miocene, Lower Miocene and Oligocene ages are source rocks in the Song Hong basin. The HC generation potential of these source rocks varies both vertically (stratigraphic) and horizontally (spatially). Oligocene sediments are potentially much better source rocks than the Miocene sediments [3, 5]. However, since the number of detailed analyses of Oligocene source rocks is limited, the relationship between the Oligocene source rocks and the encountered products is not fully documented.

Middle Miocene sediments in the Northern basin are fair source rocks with respect to organic richness, and contain mainly gas-prone kerogen type III, but in the central parts of the basin, palaeogeographic reconstructions indicate shallow marine deposition, which may be reflected in the composition of the generated HC [3]. In deeper basinal areas, Mid-Miocene source rocks entered the oil window in the late Miocene when hydrocarbon migration began. In the Southern basin the Lower Miocene source rocks contain gas-prone type III kerogen.

Oligocene sediments cover the entire basin and mainly contain the kerogen of type III. In places, especially in the southern basin, deposits containing a mixture of kerogen type I and III occur. With the exception of the Northeastern margin, Oligocene source rocks in the Southern basin have better oil potential than in the Northern basin. Most of the Oligocene and Miocene source rocks in the central parts of the basin have realised all of their HC generation potential and large-scale HC migration started from 20Ma [3].

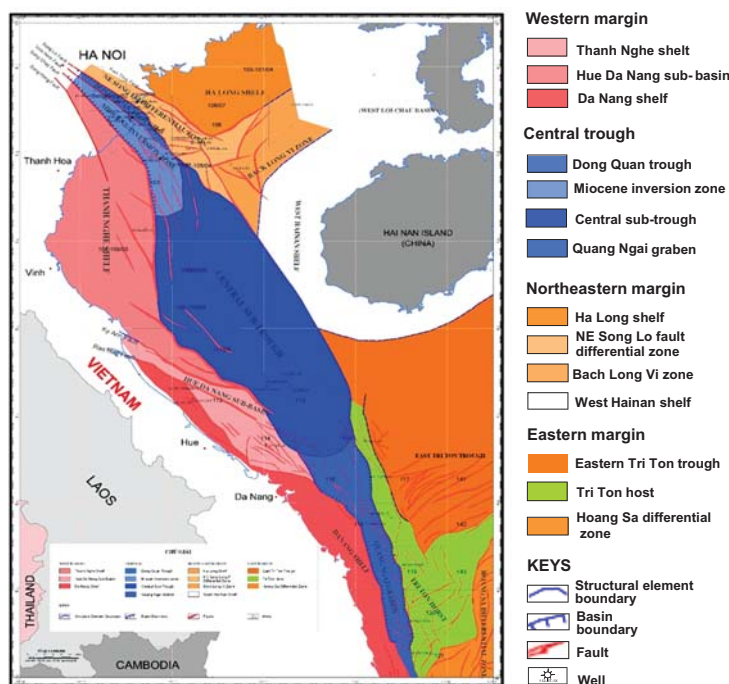


Fig.1. Main tectonic elements in Song Hong basin and adjacent area (Tru.V. and Dau N.T., 2012)

Lacustrine Oligocene source rocks that are found in outcrops at Dong Ho and on Bach Long Vi island are immature mudstones and humic coals [9, 10]. The mudstones from Dong Ho generally have a TOC content of 8 - 17%wt. and HI values of more than 500mg HC/g TOC. The organic matter is principally composed of fluorescing amorphous organic matter and liptodetrinite. The alginite with Botryococcus-morphology is present [10, 11]. The organic matter corresponds to type I kerogen. The Bach Long Vi island mudstones contain 1.55 - 7%wt. TOC and have HI values ranging from 400 to 700mg HC/g TOC. The organic matter is largely similar to that of the Dong Ho mudstones, but in addition it may contain some marine organic material (?) [6]. Studies conducted in Dong Ho area as well as offshore and onshore Bach Long Vi island (ENRECA 3 well) suggest that lacustrine shales and coaly shales of Oligocene age are excellent source rocks containing kerogen Type I and II with potential for generation of primarily oil and minor amounts of gas.

In addition, Eocene (?) source rocks may be present in the NE Song Lo fault differential zone and Bach Long Vi zone. In the neighbouring area, Eocene source rocks are present in the Chang-Liu formation in the West Weizhou basin (China) adjacent to the NE margin of the Song Hong basin. In the West Weizhou basin, source rocks are shales rich in organic matter (kerogen types I and II) with a TOC of 2.67 - 2.78%wt. and with a high petroleum potential ($S1+S2 \sim 10 - 30\text{mg/g}$; $HI \sim 200 - 600\text{mgHC/gTOC}$).

The petroleum potential of the Oligocene source rocks is better than that of the Miocene deposits. However, the number of detailed analyses of Oligocene source rocks is very limited; hence the relationship between the Oligocene source rocks and oils in the area is insufficiently documented.

The presence of source rocks in the study area is documented by analysis of rock and fluid samples from wells. The migrated oil/condensate (HC) in the wells demonstrates the following [5]:

- HC found in Devonian carbonate basement rocks in well B10-STB-1X is a proof of HC migration from source rocks into reservoir.
- The oil show in Miocene layers in the 102-CQ-1X well has a biomarker signature similar to that of one coal sample collected at a depth of 3,010 - 3,040m at the 102-HD-1X well.
- The sterane distribution of HC in the Miocene section of the 102-CQ-1X well and the sterane distribution

of DST # 3 sample (mid Miocene age) of the 103-TH-1X well are similar, but DST # 3 samples (103-TH-1X well) has a higher maturity level than samples from well 102-CQ-1X. Thus, these two HC samples can be generated from source rock which contains terrestrial organic matter (OM), but at different levels of maturation (?).

- The conspicuous even and rapid decrease in the range from C_{22} to C_{33} of the n-alkane distribution in extracts of samples from well 120-CS-1X is similar to that of HC extracted from carbonate rocks in well 119-CH-1X.

- In the Miocene section of the 118-CVX-1X well (1,150 - 1,570m) migrated HC were found: $PI > 0.3$. The source rocks in the well are immature, so the HC in the Miocene carbonate are assumed to be migrated in from thermally mature kitchens in the vicinity. Gas and oil were also encountered in carbonate in immature Miocene sections of wells 119-CH-1X, 112-HO-1X, and 118-CVX-1X.

- The 120-CS-1X well does not encounter mature source rocks, but an oil stain is present at a depth of 1,146 - 1,170m, $PI = 0.45 - 0.78$. C_{15} + chromatograms of saturated HC indicate that the source rock is mature and contains mixed kerogen. These characteristics demonstrate the presence of migrated HC in the reservoir possibly sourced from Oligocene sediments of paleo-lakes in the Quang Ngai graben (?).

3. Geochemical characteristics of oil/condensate

Compared to other Tertiary sedimentary basins of Vietnam, the Song Hong basin appears less prolific with only few petroleum discoveries. Hence, available data are insufficient for a detailed evaluation of HC-geochemistry in the basin as a whole. However, recent HC analytical data from new wells in the area (blocks 103, 106 and 107) gave new interesting information on the origin of HC. Based on the chemical and physical properties, the HC-occurrences in the Song Hong basin can be grouped:

Oil/condensate samples of the Song Hong basin are characterised by very low sulfur content ($< 0.1\%$), typical for oils generated from source rocks with non-marine organic matter. Generally, HC density in the study area is quite variable, ranging from 33°API in the B10-STB-1X well to 48°API in well 107-BAL-1X. HC in the 107-BAL-1X and 103-TH-1X wells seem to have mixed origin, including contributions from two sources, judging from biological marker data that show mixing of lacustrine oil with terrestrial condensate [7]. In the DST # 4 sample from the 103-TH-1X and 107-BAL-1X

wells the concentration of saturated hydrocarbons is high (74 - 90.68%) with very high Pristane/phytane ratio (8.18 - 30.47) indicating source rock deposited in oxic environments. Alternatively, high pristane/phytane ratio may be due to biodegradation or high maturity.

HC samples from block 112 have lower concentrations of saturates (74 - 83%) and the pristane/phytane ratio is lower, 4.8 - 7.7. Samples DST # 1 and DST # 3 from the 103-TH-1X and 106-YT-1X wells have low concentrations of saturated HC (Fig.2), and the pristane/phytane ratio is moderate (2.33 - 5.71).

Samples from wells 118-CVX-1X and 119-CH-1X have the lowest concentration of saturated HC (37.1 - 54.6%), high concentrations of aromatic HC (40.39-57%) and low pristane/phytane ratios (< 2). On the diagrams, samples from wells B10-STB-1X, 106-YT-1X, 107-BAL-1X, and 107-PA-1X are marked in green; wells in blocks 102 and 103 are marked in red; wells in blocks 112, 114 and 115 are marked in blue; and wells in blocks 118, 119, 120 and 121 are marked in purple.

On the chart of group type composition of the HC (saturate-aromatic-heavy component), all samples were concentrated to the left of the chart indicating the normal HC, not degraded (Fig.2), thus any doubts that biodegraded organisms cause high values of pristane/phytane can be erased. However, two separate groups have been recognised: 1) the sample group from blocks 118 and 119, DST # 1 and DST # 3 in well 103 TH-1X; 2) the group of samples from wells B10-STB-1X and 107 BAL-1X, DST # 4 at well 103 TH-1X and from the wells in block 112. Particularly, the sample from 106-YT-1X which is separated from the groups may be indicator of higher maturity level (?).

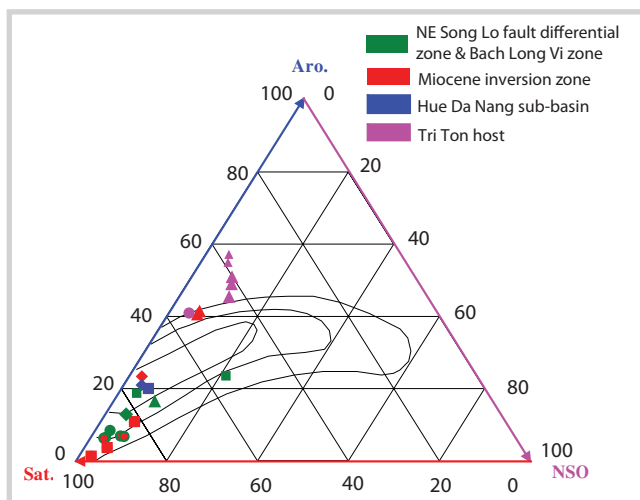


Fig.2. Group type composition of oil samples in the Song Hong basin

Fig.3 demonstrates the relationship between pristane/phytane and nC_{17}/nC_{18} , the distribution of the samples showed more clear groups. Most samples from blocks 118, 119 and 120 belong to group distribution in the transition zone, while samples from 103-TH-1X, B10-STB-1X and remaining wells are distributed into two groups even though they all belong to the terrestrial peat swamp environment. The Biomarkers from mass spectrometry analysis data (GC-MS) can further evaluate the input and maturity of original OM (source rock). The chart of $C_{27-28-29}$ sterane relationship (Fig.4) indicates that the samples from 102-CQ-1X and 112-HO-1X are distributed in the terrestrial; samples from 103-TH-1X are distributed in the

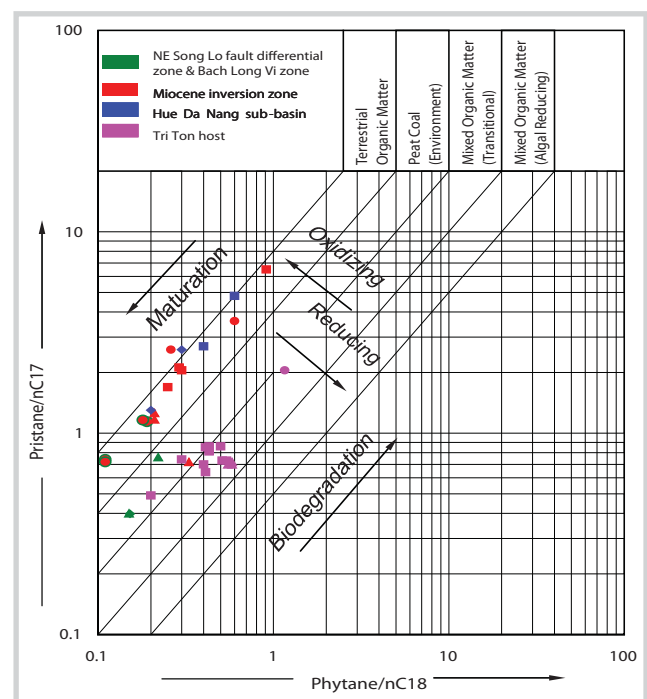


Fig.3. The correlation between Pristane/ nC_{17} and Phytane/ nC_{18} ratio HC samples in Song Hong basin

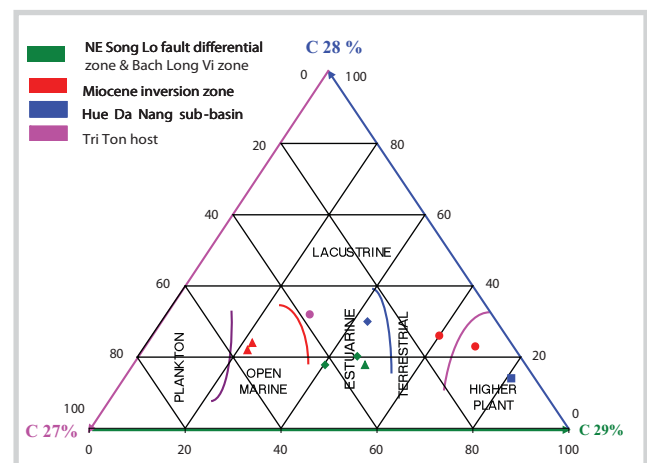


Fig.4. The correlation between C_{27} , C_{28} and C_{29} steranes HC samples in Song Hong basin

open marine area. The remaining samples are distributed in the estuarine one.

Correlation chart of Ts/Tm ratio and Oleanane index of hopane in saturate HC (Fig.5) shows samples from the wells at blocks 106 and 107 and the B10-STB-1X well (green symbols in red ellipse line) distributed in the region of higher lacustrine than samples from blocks 102, 103 and

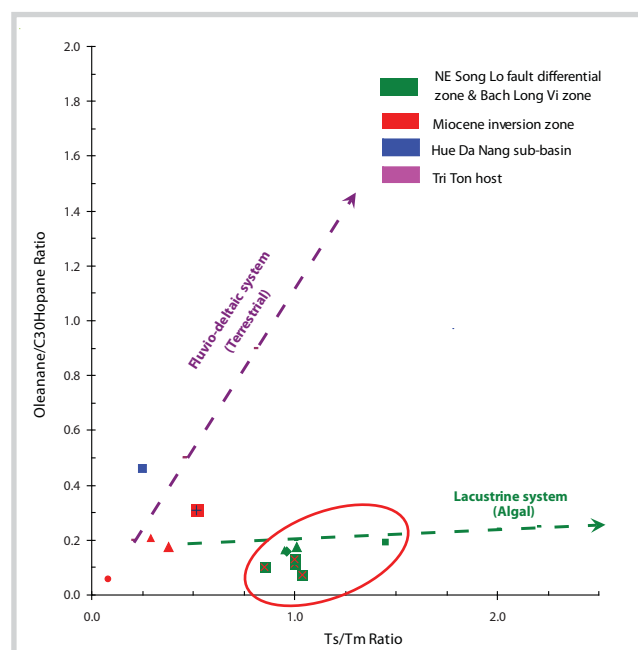


Fig.5. The correlation between Oleanane/Hopane and Ts/Tm ratio HC samples in Song Hong Basin

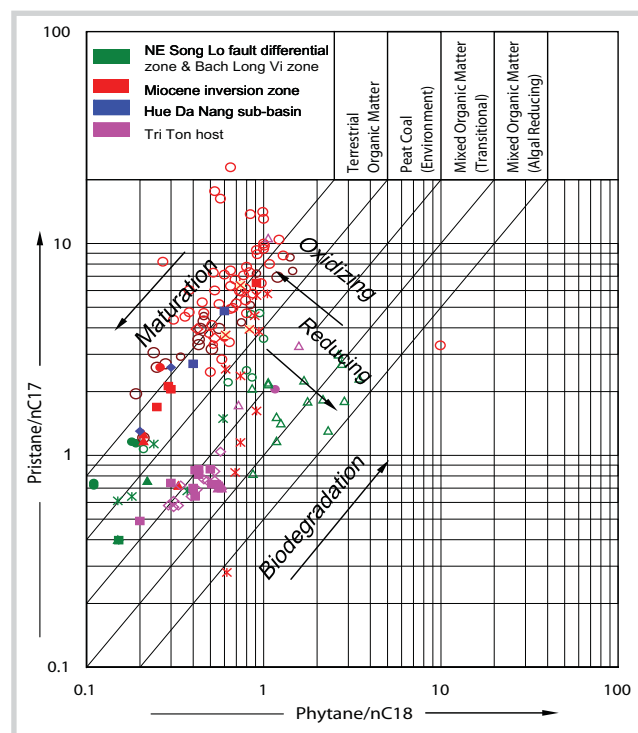


Fig.6. The correlation between Pristane/ nC_{17} and Phytane/ nC_{18} ratio HC and source rock samples in Song Hong basin

112 (red and blue symbols). This distribution is consistent with Fig.2 and Fig.3. Especially, the sample from well 106-YT-1X is distributed in the lacustrine system (algal) but separated from the group, perhaps due to its higher maturity level Tm transformed into Ts and resulting in the high Ts/Tm ratio. As the result, this sample is distributed on the right side of the chart (Fig.5).

4. Migration possibility of oil/condensate from the source rocks

In order to compare oils and source rocks, in the following oils are represented by filled symbols, whereas source rocks are represented by open symbols, with wells from the same areas shown in identical colour. The B10-STB-1X, 106-YT-1X, 107 BAL-1X, and 107 PA- 1X wells are shown in green; the wells in blocks 102 and 103 in red; the wells in blocks 112, 114 and 115 in blue; and the wells in blocks 118, 119, 120 and 121 in purple. Figs. 6 through 8 show the relationship of source rocks and HC in the study area. HC samples and extracts from source rocks in the same area (with symbols of the same colour) are often distributed along a maturity trend (Fig.6). This suggests a genetic relation between HC and source rocks. And, this distribution shows on proven migration distance of HC from source rocks to traps may not be large (?)

The preponderance of lacustrine input is clear in both oil and source rock data in the NE margin compared to other areas in the Song Hong basin (Figs.6, 7 and 8). Unfortunately no biomarker data are available for samples from the NE Song Lo differential zone and Bach Long Vi zone.

As mentioned above, five fluid samples of the 107-BAL-1X, 106-HR-1X, 106-HR-2X, and 106-YT-1X wells were

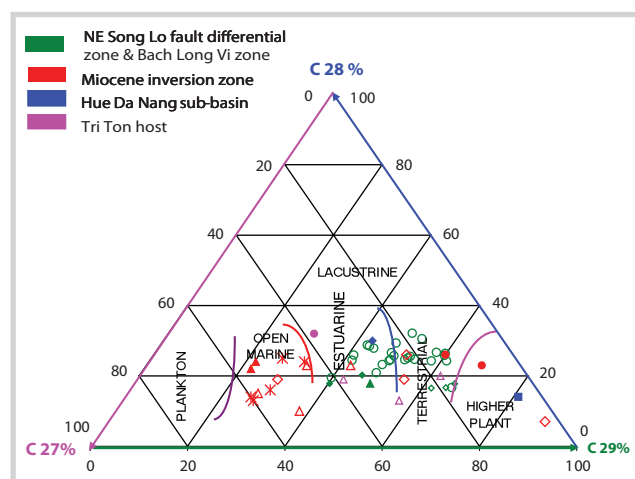


Fig.7. The correlation between C_{27} , C_{28} and C_{29} steranes HC and source rock samples in Song Hong basin

collected and analysed with respect to bulk properties and separated into four such fractions as saturate, aromatic, resine and asphaltene on liquid chromatography by using silica column. GC (Gas chromatography), GCMS (Gas chromatography-Mass spectrometry) and GCMSMS have been carried out on saturate and aromatic fractions.

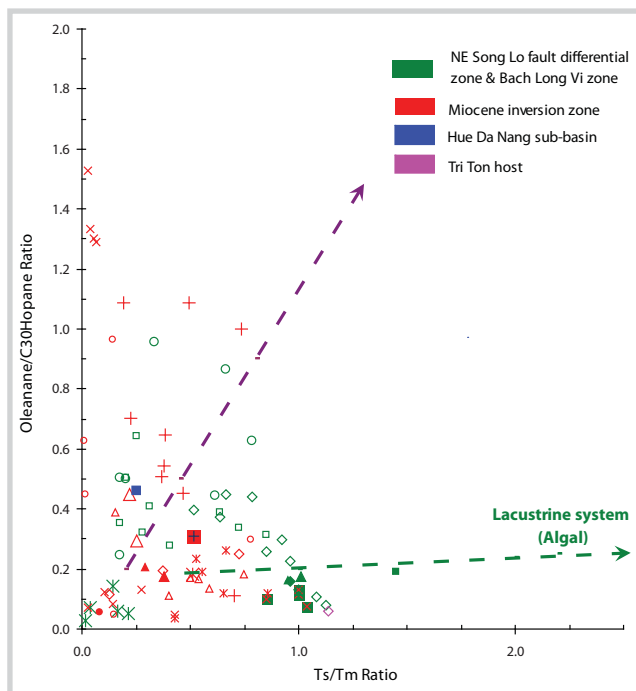


Fig.8. The correlation between Oleanane/Hopane and Ts/Tm ratio HC and source rock samples in Song Hong basin

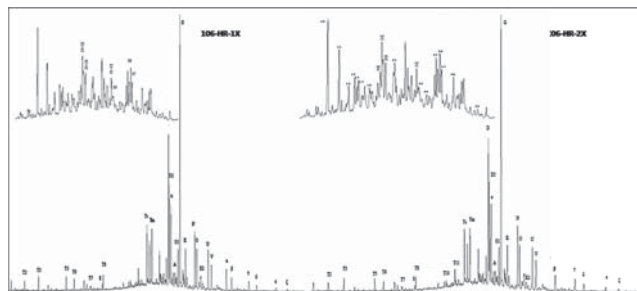


Fig.9. GC-MS chromatograms of two oil samples from 106-HR-1X and 2X wells

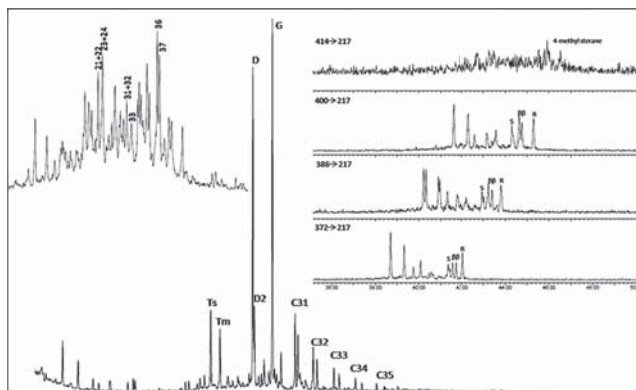


Fig.10. GCMSMS chromatograms of DST#3 from 107-BAL-1X well

The API results show that fluid samples of 107-BAL-1X and 106-YT-1X are condensates but two fluid samples of 106-HR-1X and -2X are crude oils with low sulphur contents and a group type composition in the normal oil range with respect to HC concentration (Fig.2).

The two oil samples collected from wells 106-HR-1X and -2X have similar characteristics with typical lacustrine geochemical signatures, including medium Pristane/Phytane ratios (2.95, 2.90 in each) and "lacustrine" distributions of hopanes (Fig.9). Besides, they are characterised by the presence of 4-methyl C_{30} Sterane (peak 42), tricyclic terpane distribution with some lacustrine signature and predominance of C_{27} and C_{29} steranes over C_{28} steranes (Fig.9). These features suggest that these oils are mainly derived from lacustrine algal organic matter.

The condensate fraction ($< nC_{20}$) of samples from well 107-BAL-1X shows very high pristane/phytane ratios (8.18 to 30.47), which is typical for the fluvio-delta depositional environment with high oxidation level. They show relatively high BTX (Benzene-Toluene-Xylene) content, high isoprenoid abundance, significant anthracene and Me-anthracene concentrations in the aromatic fraction, all of which suggest the condensates were mainly generated from terrestrial source rock [7]. In contrast, heavier fractions show evidence to suggest input from lacustrine algae, including the presence of tricyclic terpanes, 4-methyl C_{30} sterane and "lacustrine" distribution of hopanes (Fig.10). Moreover, cross-plotting oleanane/hopane ratio versus the Ts/Tm ratio (Fig.5) shows all samples of 107-BAL-1X to distribute in the lacustrine field. The same features are found in the condensate from 106-YT-1X (Fig.2). However, this condensate has some different properties with respect to bulk composition (Fig.2) and biomarkers (Fig.5) that need more investigation to evaluate.

5. Conclusions

- Some oil groups could be recognised in the Song Hong basin:
 - + Hydrocarbon with mainly terrestrial input found in blocks 102 and 103 (*Miocene Inversion Zone*);
 - + Hydrocarbon with mainly lacustrine input encountered in blocks 106 and 107 and well B10-STB-1X (*NE Song Lo differential zone and Bach Long Vi zone*);
 - + Hydrocarbon with mainly terrestrial input distribute in block 112 (*Hue Da Nang Sub-basin*),
 - + Hydrocarbon from blocks 118 and 119 and

migrated HC found from block 120 (*Tri Ton horst*) and HC from block 113 (*Central Sub-trough*).

- Oils and source rocks were encountered in NE Song Lo differential zone and Bach Long Vi Zone with the most prominent lacustrine input compared to other structural elements of the Song Hong basin.

- The distribution of oil/condensate groups and source rocks in the different structural elements of the Song Hong basin shows close relationships, suggesting short migration distances.

- The distribution of source rocks in the Song Hong basin, as well as their geochemical characteristics, show spatial variation. The role of each source rock in supplying HC into the reservoirs in the study area is clarified only when analysing the results of geochemical modelling and geochemical characteristics of the group of oil/condensate (HC). The spatial distribution of the HC groups in relation to the geological structures of the Song Hong basin is a matter in need of further research.

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EXPERIMENTAL STUDY OF HYDROMECHANICAL BEHAVIOUR OF UNCONSOLIDATED AND WEAKLY CONSOLIDATED RESERVOIR ROCKS

Nguyen Van Hung¹, Le Phuoc Hao¹, Nicolas Gland²

¹Petrovietnam University, Vietnam

²IFP Energies Nouvelles, France

Email: hungnv@pvu.edu.vn

Summary

This present paper is the first part of a general work on the characterisation of the hydromechanical behaviour of unconsolidated materials and weakly consolidated sandstones. Laboratory experiments under hydrostatic loading and proportional triaxial stress paths at fixed ratio K (defined as the ratio of horizontal to vertical stress increments) have been performed on clean unconsolidated materials - coarse rounded grains (glass beads) and angular grains (Durance sand), and on a fine to medium grained weakly cemented layered sandstone (Otter Sherwood sandstone). Different mechanical behaviours were evidenced for each material. While the yield stress under hydrostatic loading can be predicted by a theoretical model for reference analog material such as glass beads, there is a significant discrepancy for the sand with angular grains, and for the sandstone due to its heterogeneous composition. The pore collapse and volumetric strain were observed to be strongly controlled by the stress path.

Permeability measurements were performed in the vertical directions on core samples. Our results have shown that the absolute vertical permeability value must be estimated from intermediate pressure measurements rather than across the sample end surfaces. The results also show that the permeability evolutions follow closely the material deformation and are controlled by both volumetric and shear strains. For stress path parameter $K > 0.4$, the permeability is solely controlled by the mean effective stress and resulting volumetric strain. Otherwise, the permeability change is intermediate between the onset of inelasticity and the maximum curvature on the stress-strain curve. As the stress path parameter decreases, the influence of deviatoric stress becomes dominant as highlighted on isopermeability contours in the P' - Q stress diagrams.

Key words: Stress path, hydromechanical, cam-clay modified, compaction.

1. Introduction

It is well known that the mechanical compaction of porous rocks can induce inelastic deformation and irreversible changes of porosity. At the time scale of geological processes, the burial of sedimentary rocks leads to compaction and variable consolidation degree; at shorter time scale, the industrial underground activities, such as petroleum production and gas storage can affect the reservoir rocks integrity. For instance, pressure depletion associated with hydrocarbon production can induce large strains and plastic deformations in the reservoirs, with serious consequences such as subsidence, well failures, permeability reduction, and reservoir impairment. Approximately 90% of the world's oil and gas wells are drilled in sandstone reservoirs [1] and many new reservoirs are discovered in the North Sea, Shetland Island U.K, Gulf of Mexico, off-shore Angola and Brazil in unconsolidated sands or weak sandstones [2] more prone to compaction. Thus it is important to have a fundamental understanding of the mechanics of compaction for this kind of materials.

Several laboratory studies have focused on the compaction behaviour of siliciclastic rocks (mainly

sandstones) [3 - 6] and carbonates [7 - 9]. Under isotropic compression, macroscopic inelastic compaction associated with the breakage of particles was identified for most granular soils at high stresses [2] and porous rocks [10]. Earlier and recent studies focused on determining a correlation between microstructural parameters and the critical pressure P^* at the onset of grain crushing under hydrostatic compaction loading [3, 10, 11]. A power law relating grain size times porosity to the critical pressure was identified for glass beads, porous sandstones [3] and rounded (Ottawa) sands [11]. On the basis of a Hertzian fracture model, and an homogenisation scheme, Zhang et al. [10] predicted an exponent equal to $n = -1.5$ for that power law. On the basis of recent experimental results on rounded quartz sand with selected range of sizes, Karner et al. [11] found that the P^* value depends on the grain radius (d) via a power-law relationship with exponent $n = -0.68$; accounting for the porosity, this result agrees with the former model.

For more general deviatoric stress paths, once the pressure reaches the yield point, the plastic strains are accommodated either through brittle shear failure (either

dilatant or compactant behaviour) or compactive pore collapse. As the permeability is mostly systematically measured in the direction of maximal vertical stress (vertical permeability), an important reduction of one to two order of magnitude is generally measured; Enhancement of permeability for measured vertical permeability has rarely been observed [12] only for extreme deviatoric stress paths.

In order to investigate in the laboratory the coupled mechanisms of reservoir compaction and permeability evolution during the depletion, many authors [6, 13] assumed that the reservoir compacts following uniaxial strain, in so-called oedometric, conditions, i.e. without lateral strains. However, field observations performed by Rhett et al. [12]; Hettema et al. [14] and Ruistuen et al. [15] have confirmed that stress state evolution could be more complex and rarely satisfy purely uniaxial conditions. Rhett et al. [12] introduced a stress path parameter K , defined as the ratio between the rate of effective horizontal stress increase $\Delta\sigma'_h$ and the rate of effective overburden stress increase $\Delta\sigma'_v$, from initial reservoir conditions, which accounts for observed field stress state evolutions during the production.

The behaviour of materials has traditionally been tested within the context of soil mechanics. Thus, the laboratory studies have usually investigated mechanical behaviour under low pressure hydrostatic conditions. In the context of petroleum industry, the interesting reservoir rocks are commonly located at depths down to several kilometres [9, 13, 16], therefore there is the need of testing uncemented sands or weak sandstones also at high pressures (until around 100MPa effective pressures). Previous studies have shown that the behaviour of such rocks at high pressure has much in common with simple frameworks such as Critical State Soil Mechanics [17 - 19].

Mainly in the petroleum and geomechanics literature, several authors [14, 15, 20 - 26] have investigated experimentally the effect of pressure and stress path in this range of interest on the compaction and sometimes on the coupled permeability evolution; yet a general correlation to predict the compaction and permeability under different stress path is missing. For permeability measurements under stress it is important to pay attention to the "end effects" which can sometimes induce errors preventing to get the "true" vertical permeability value [27].

In this paper, the authors report an experimental hydromechanical study on a high porosity, high

permeability unconsolidated river sand and a weakly consolidated Triassic outcrop sandstone using a special experimental setup used for combining rock compaction and fluid flow capabilities. Our goal is to provide a comprehensive database to characterise the stress-dependent properties of unconsolidated and weakly consolidated geomaterials. This data set will be used to define and build an accurate model in a following paper.

In the first part, hydrostatic tests were performed on both materials (also on a reference glass beads material to calibrate the experiments) in order to compare their respective yield pressures with published experimental results and the prediction of a model proposed by Zhang et al. [10]. In the second part, several stress path compaction tests have been carried out to identify their respective yield stresses. These results were used to determine the plastic yield surface and its evolution with material hardening. Finally, the authors aim to further understanding the vertical permeability evolutions under deviatoric stress paths.

2. Experimental methodology and materials

2.1. Experimental setup

The hydraulic triaxial cell used for this study (Fig.1) has been previously used by Gland et al. [8] to measure vertical and horizontal permeabilities for consolidated rocks such as sandstones and carbonates. The cell is operated with two high-pressure pumps (up to 69 MPa) to control independently the confining $P_c = \sigma_r$ and axial σ_a pressures in order to apply different stress paths. The pore pressure regulation is achieved by a back pressure device while the flow is generated by a lower pressure pump (up to 25MPa).

In order to measure the large vertical and radial strains of unconsolidated material, the authors used a couple of external linear variable differential transformer (LVDT) sensors (range $\pm 5\text{mm}$) fastened to the upper mobile piston and a dual cantilever sensor (range $\pm 3\text{mm}$) fastened to the nitrile sleeve inside the cell. The volumetric (ϵ_v) and deviatoric (ϵ_Q) strains are calculated from the axial (ϵ_a) and radial (ϵ_r) strains as:

$$\epsilon_v = \epsilon_a + 2\epsilon_r \quad (\text{Eq.1})$$

$$\epsilon_Q = 2/3(\epsilon_a - \epsilon_r) \quad (\text{Eq.2})$$

In this study, the authors report only vertical permeability data measured in the axial direction of maximal stress. Two pumps generate either oil or brine flow rates Q into the samples (pressure up to 15MPa and

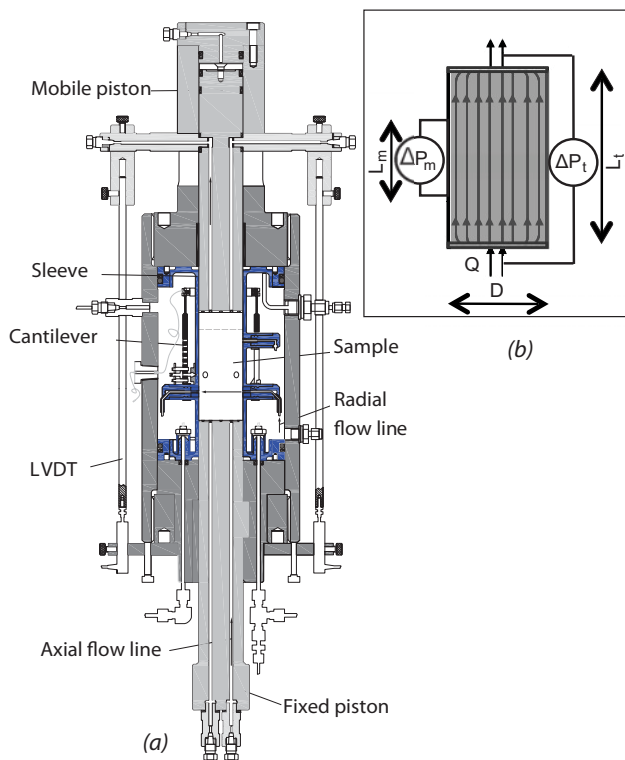


Fig.1. Schematic diagram of the triaxial cell installed at IFP Energies Nouvelles (modified from ErgoTech)

35MPa respectively). Two permeability values are actually measured (Fig.1b): $k_{V,T}$ over the total length of the sample ($L_T \sim 80\text{mm}$) and $k_{V,M}$ over an intermediate length ($L_M = 60\text{mm}$) corresponding to the spacing of the pressure ports located radially on the sleeve. The latter avoids hydro-mechanical end-effects and also enables to measure very high permeable geomaterials such as coarse grained sands. Two pressure differential devices are connected to the pistons flow lines and to the pressure ports to measure the pressure drops simultaneously ΔP_T and ΔP_M . The permeabilities are derived from Darcy's law:

$$k_{V,T/M} = Q \left(\frac{\mu}{\Delta P_{T/M}} \right) \left(\frac{L_{T/M}}{S} \right) \quad (\text{Eq.3})$$

To control and measure the pore pressure P_p respectively under drained and undrained conditions, a pressure sensor is connected to the bottom piston flow line.

The cell and flow lines are set inside an oven to better control the temperature of the experiments when required.

2.2. Strategy for selecting the materials for the study

As mentioned above, the triaxial cell has been used before to study the behaviour of consolidated rocks. For this study, the authors focus only on the hydromechanical behaviour of unconsolidated sand and weakly consolidated sandstone.

Firstly, the authors chose a simple commonly used reference material on the basis of existing models, glass beads which have been studied by many authors [Garbrecht 1993; Yin and Dvorkin 1993] cited in [3, 10]. This material was tested generally under hydrostatic loading and agrees well with the Zhang et al., 1990's model [10] for the prediction of the critical pressure based on Hertzian contact theory and crack propagation mechanics. Thus glass beads have been used as a model material in order to calibrate our experimental procedure.

Secondly, starting from the knowledge of other experimental studies [5, 11, 28] we were looking for an analogue material for the study of unconsolidated sands. Many authors [11, 13] have worked on Ottawa sand from the St. Peter Sandstone deposits in Illinois, an almost pure quartz coarse-grained rounded sand. In this study, we preferred to choose a fluvial sand from the Durance river (France) as a natural analogue of unconsolidated sands. The Durance sand (DS) is also quartz rich coarse grained sand, but the grains are angular, which is more common in natural geological environments.

For both unconsolidated materials, we want to make sure that the transition zone between elastic and non elastic regimes can be reached within the range of capability of our pressure vessel and preferably between 20 to 40MPa. The beads and sand grain size were chosen accordingly on the basis of correlation obtained from studies on glass beads and Ottawa sands [3, 10, 11]. It is worth to mention that both unconsolidated materials of equivalent grain size have thus high permeability.

Finally, we studied the hydromechanical behaviour of very weakly consolidated sandstone, with a heterogeneous mineralogical content, the Triassic Otter Sherwood sandstone (called hereafter OSS). Otter Sherwood sandstone outcrops in Wessex, South-West of England, it was directly sampled from Ladram Bay cliffs. This sandstone belongs to the family of Triassic Sherwood sandstone group [29, 30] being the reservoir rocks of the nearby onshore Wytch Farm oil field in Dorset, which main producing units are located at a depth of approximately 1,500m [31, 32].

2.3. Sample preparation

Two kinds of preparation were followed according to the different materials consolidation.

Unconsolidated sand: The sand was first sieved to select an appropriate narrow grain size distribution. The unconsolidated samples were prepared directly in the

Table 1. Initial conditions of tests

Type	Unconsolidated		Weakly Consolidated
	Beads	Sand	OSS
Permeability test	$P_c = 3\text{MPa}$ $P_p = 0.5\text{MPa}$ SF: O	$P_c = 3\text{MPa}$ $P_p = 0.5\text{MPa}$ SF: O	$P_c = 2\text{MPa}$ $P_p = 0.5\text{MPa}$ SF: B
Mechanical test	$P_c = 3\text{MPa}$ $P_p = 0.5\text{MPa}$ SF: O	$P_c = 0.7\text{MPa}$ $P_p = 0.5\text{MPa}$ SF: B	

P_c : Confinement; P_p : Pore pressure

SF: Saturating fluid; O: Oil; B: Brine

sleeve of diameter $D = 38.1\text{mm}$. The sample assembly was gently vibrated by tapping on the bottom piston so as to precompact the material and minimise the initial porosity ϕ_o . In a first stage all samples have been compacted at an initial hydrostatic pressure. Purely mechanical tests were performed in both dry and brine saturated conditions while hydro-mechanical tests were performed with oil as saturating fluid; for the measurements of very high permeability, a viscous oil (MARCOL 172, $\mu = 26\text{cp}$ at 40°C) was selected to reduce the mobility ratio k/μ and allow differential pressure (dP) measurements. Samples were saturated after minimum 3 hours of vacuum. The cell and the system lines were regulated at 40°C with the oven in order to get a thermal stability and tune oil viscosity for dP sensors. Finally, a slight flow was maintained through the sample during one night to insure a perfect saturation by flushing residual trapped gas bubbles, while the pore pressure was regulated at $P_p = 0.5\text{MPa}$ using a back-pressure regulator (Table1).

Weakly consolidated sandstone: The outcrop Otter Sherwood sandstone samples were cored perpendicular to the apparent bedding plane, with a nominal diameter of $D = 38.1\text{mm}$ and cut with a length of $H \sim 80\text{mm}$. All samples were dried inside an oven regulated at 60°C for at least 48 hours. The density profiles of each dry sample were then measured using an X-ray CT-scanner. The samples have been selected for the hydro-mechanical tests with respect to their homogeneous density profiles to avoid any effect of structural heterogeneity. Those samples required careful handling and manipulation while being set in the sleeve and cell due to their very weakly consolidated nature. Preliminary hydrostatic pressure was set as (Table1) in order to ensure sealing of the core sleeve on the sample and proper setting of the radial

extensometer. Except one mechanical test performed in dry condition, all others hydro-mechanical tests were performed using NaCl brine at 20g.L^{-1} concentration. The saturating procedure is similar to the sands. Those tests were performed at the laboratory regulated temperature close to 20°C ; the pore pressure was regulated at $P_p = 0.5\text{MPa}$ as well (Table1).

At that point, deformation LVDT sensors and cantilever are initialised and a compression experiment is ready to begin.

2.4. Microstructural and mineralogical properties

Unconsolidated sand: The Durance sand was sieved with sieve fraction $(1,000 - 1,100)\mu\text{m}$ in order to obtain a grain size distribution close to the one of the reference glass beads ($\sim 1,000\mu\text{m}$). The actual grain size distributions was characterised by Particle Laser Diffraction method (giving a volume equivalent dimension) using respectively refraction index of the minerals glass and quartz; respective rounded and angular shape of the grains may have some influence on the measured size distribution of reference glass beads and sieved Durance sand.

Weakly consolidated sandstone: While the sand is considered homogeneous in composition with almost exclusively quartz content, mineralogical content of the Otter Sherwood sandstone is much more complex. Using X-ray diffraction, Svendsen and Hartley [33] showed that this sandstone is composed of quartz (mean 30%, range 26.5 - 43.5%), feldspar (mean 18.3%, range 13 - 26%), detrital clays dominated by illite (mean 11.8%, range 3.5 - 29%) and some Micas (mean 2.1%, range 0 - 7%). The authors confirmed this mineralogy by a petrography study on thin sections; from SEM imaging, we estimated percentages of quartz and feldspar of 38% and 18% respectively. For Otter Sherwood sandstone particle size distribution were estimated on crushed samples using major mineral (quartz) refraction index; it presents a much wider distribution of grain sizes but this result should be considered as a qualitative information only due to the mineralogical heterogeneity of the material (Fig.2).

Fig.3 shows micrographs obtained under optical microscopy for the three materials, in which one can see the coarse rounded grains of the glass beads, the coarse angular grains of Durance sand, and the fine grained Otter Sherwood sandstone with its heterogeneous composition. For the latter, the authors also observe laminations with finer grains and reduced porosity.

2.5. Petrophysical parameters

The petrophysical parameters, porosity and permeability, were determined for each material.

Unconsolidated sand: For the Durance sand, the porosity of each close packing was estimated at the initial hydrostatic pressure from the bulk geometrical volume of the sleeve (corrected by the initial deformation) and the mass of sand grains. The initial permeability $k_{v,M}$ was then measured by the steady-state multi flow rates technique; yet, because of the very high permeability of the sand, the additional pressure drops of the system flow lines and the sample end effects covers the pressure differential due to

the flow inside sand packing; the only way to sample this pressure differential for such highly permeable sand was by taking advantage of the local pressure ports molded on our sleeve and connecting them to an accurate ± 15 mbar dP sensor. It is worth noting that it is clearly not a trivial measurement (Table 3).

Weakly consolidated sandstone: For the weakly consolidated Otter Sherwood sandstone, the porosity measurement was obtained by the saturation technique (volume of fluid injected in the pore space under vacuum corrected from dead volumes), as well as by various conventional core analysis methods on smaller samples, such as helium porosity, nuclear magnetic resonance (NMR) porosity and Mercury porosimetry. The initial permeabilities were also measured by the steady-state multi flow rates technique; the two measurements $k_{v,T}$ and $k_{v,M}$ were obtained simultaneously using the ± 400 mbar dP sensor connected on the system flow lines and the ± 75 mbar dP sensor connected to the local pressure ports (Table 4).

Table 2. Summary of measured parameters for the different tests

Sample	Porosity (%)	Permeability (D)
Sovitec Glass Beads	~37	$\langle k_v \rangle \sim 600 \pm 60$
Durance Quartz sand	~42	$\langle k_v \rangle \sim 600 \pm 72$
Otter Sherwood sandstone	$\sim 33 \pm 0.3$	$\langle k_h \rangle = 0.35 \pm 0.07$ $\langle k_v \rangle = 0.2 \pm 0.03$

Table 3. Durance sand

Samples	Stress Path K	ϕ (%)	$k_o(M)$	$k_v(M)$ (at P_{max})
			(mD) $\times 10^3$	(mD) $\times 10^3$
DS (O)	1.0	39.0	627	33
DS (O)	0.8	38.2	614	31
DS (O)	0.6	38.7	610	6
DS (O)	0.4	38.5	605	6
DS (O)	0.3	38.9	-	-
DS (O)	0.2	38.6	620	274

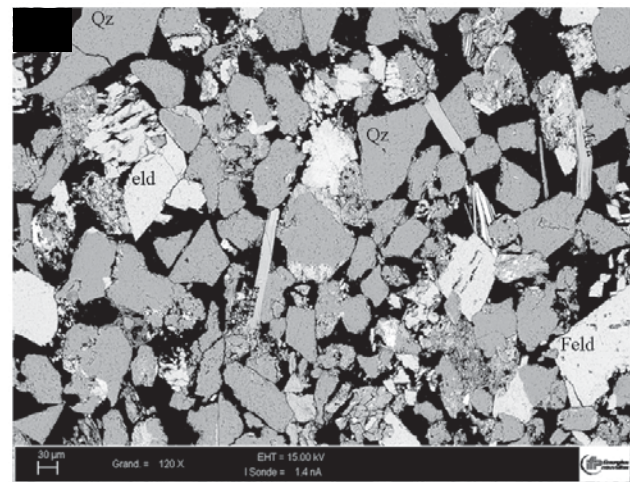
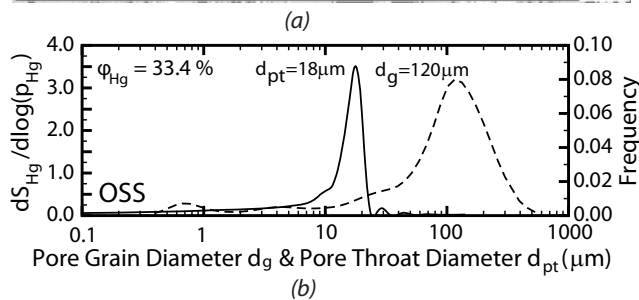


Fig.2. Grain size distributions from Laser Particle Diffractometry (a), Hg porosimetry on Otter Sherwood sandstone (solid line) and grain size distribution (dashed line) (b)

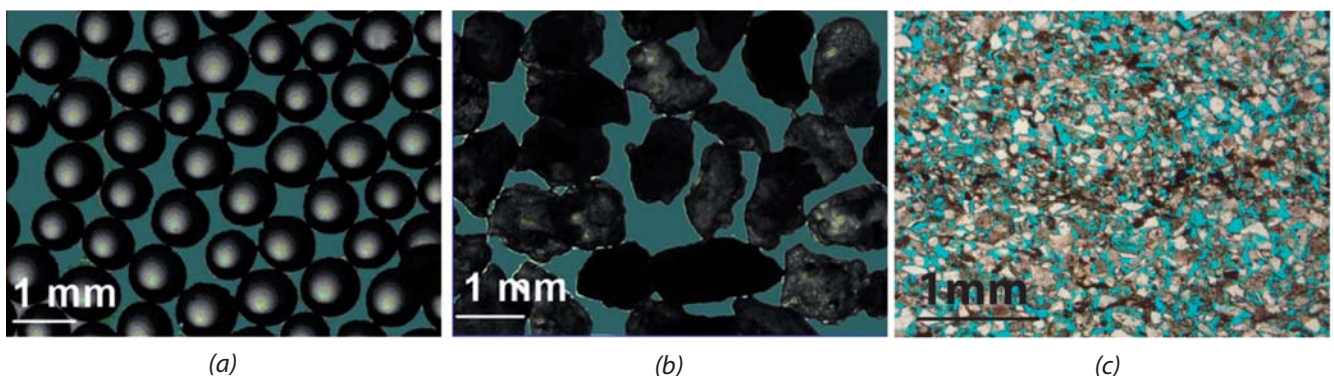


Fig.3. Micrographs from optical microscopy on glass beads (a), Durance sand (b) and Otter Sherwood sandstone (c)

Table 4. Otter Sherwood sandstone

Samples	Stress Path K	Φ (%)	$k_{vo}(T)$ (mD)	$k_{vo}(M)$ (mD)	$k_{vo}(T)/k_{vo}(M)$	$k_v(T)$ at P_{max} (mD)	$k_v(M)$ at P_{max} (mD)	$k_{vo}(T)/k_{vo}(M)$
OSS V (W)	1.0	34.1	151	200	0.76	5	-	-
OSS V (W)	0.8	31.0	168	215	0.78	20	25	0.8
OSS V (W)	0.6	33.7	208	258	0.81	31	41	0.76
OSS V (W)	0.4	33.4	150	185	0.81	16	-	-
OSS V (W)	0.3	32.0	129	150	0.86	-	-	-
OSS V (W)	0.2	31.0	155	222	0.70	-	-	-
OSS V (W)	0	33.5	147	164	0.90	-	-	-

Uncertainties: on porosity and permeability measurements were calculated using error propagation equations as shown in [8]. The average petrophysical properties of each geomaterial are reported in (Table 2).

3. Experimental results

3.1. Hydrostatic compaction

For each material, a reference hydrostatic compression experiment was performed first, in drained condition, with the pore pressure maintained constant at 0.5MPa. The pressure was increased at a rate of 0.1MPa.min⁻¹ up to $P \sim 60$ MPa while monitoring strains evolutions.

3.1.1. Critical pressure and Zhang's model

The three hydrostatic compaction curves (mean effective stress - volumetric strain) of glass beads, Durance sand and Otter Sherwood sandstone are shown in Fig.4. The deformations are strictly compactant. Each curve presents an inflection point corresponding to a critical effective stress beyond which the decrease of volumetric strain is steeper marking the transition between the elastic and plastic regimes. As shown in Fig.4a, while the linear part of the curves (elastic regime) is clearly identifiable for the glass beads and the Otter Sherwood sandstone, it is not as straightforward for the Durance sand. The onset of plastic collapse (initiation of pervasive grain crushing), so-called critical pressure P^* [10], is picked as the endpoint of the linear evolution of the volumetric strains. For the glass beads, this value is close to $P^* = 29.5$ MPa and for the Otter Sherwood sandstone the onset of plastic collapse occurs at $P^* = 39.5$ MPa. For the Durance Sand, the strain curve does not show any sharp variation of the curvature of the stress-strain curve, making difficult a clear picking of the deformation regime change. Consequently to identify a yield stress, the authors had to use another criterion following the work of Mesri et al. [28], the point of maximum curvature of the stress-strain curve $Max(\epsilon_v'' / (1 + \epsilon_v'^2)^{3/2})$ (Fig.4b) highlights

the method of determination of the yield stress value for the Durance sand, leading to the value $P^* = 9.8 \pm 0.6$ MPa.

The experimental values of P^* can be compared to the prediction of Zhang et al., 1990 model [10] based on the Hertzian contact theory and crack propagation mechanics. Zhang et al. [10] proposed a power law describing the dependency of the critical pressure with microstructural attributes: $P^* \sim (\phi R)^n$, where ϕ is the porosity, R is the mean grain radius and $n = -1.5$. This power law relation has been tested and validated on glass beads, on consolidated porous sandstones by Wong et al. [3] and more recently on rounded quartz sand by Karner et al. [11]. Using this law with the measured porosity and the mean grain radius determined by Laser Diffraction (Fig.2) and confirmed by thin sections and SEM images analysis, the predicted critical pressures P^* are roughly 30MPa for the glass beads, 20MPa for the Durance sand and 800MPa for Otter Sherwood sandstone. The model is in good agreement with the critical pressure measured on the reference glass beads but overestimates by a factor 2 the critical pressure value of Durance sand, and by more than one order of magnitude that of Otter Sherwood sandstone (Fig.4c). The reason for such a discrepancy can be the heterogeneous nature of Otter Sherwood sandstone and the sharpness of grains in the Durance sand that are not in agreement with the assumptions of the model.

An additional hydrostatic compression test was performed on Durance sands by sieving grain sizes twice smaller $d_g \sim 0.55$ mm with the expectation of increasing P^* by few tens of MPa with regard to the cell pressure range. While the maximum curvature point could be identified for the sand with bigger grain sizes Fig.4d, the inflection point disappear with smaller grain sizes. We thus decided to keep the former grain sizes for the study.

3.1.2. Damage analysis

- Unconsolidated sands: After unloading the samples deformed hydrostatically up to 60MPa and specimen

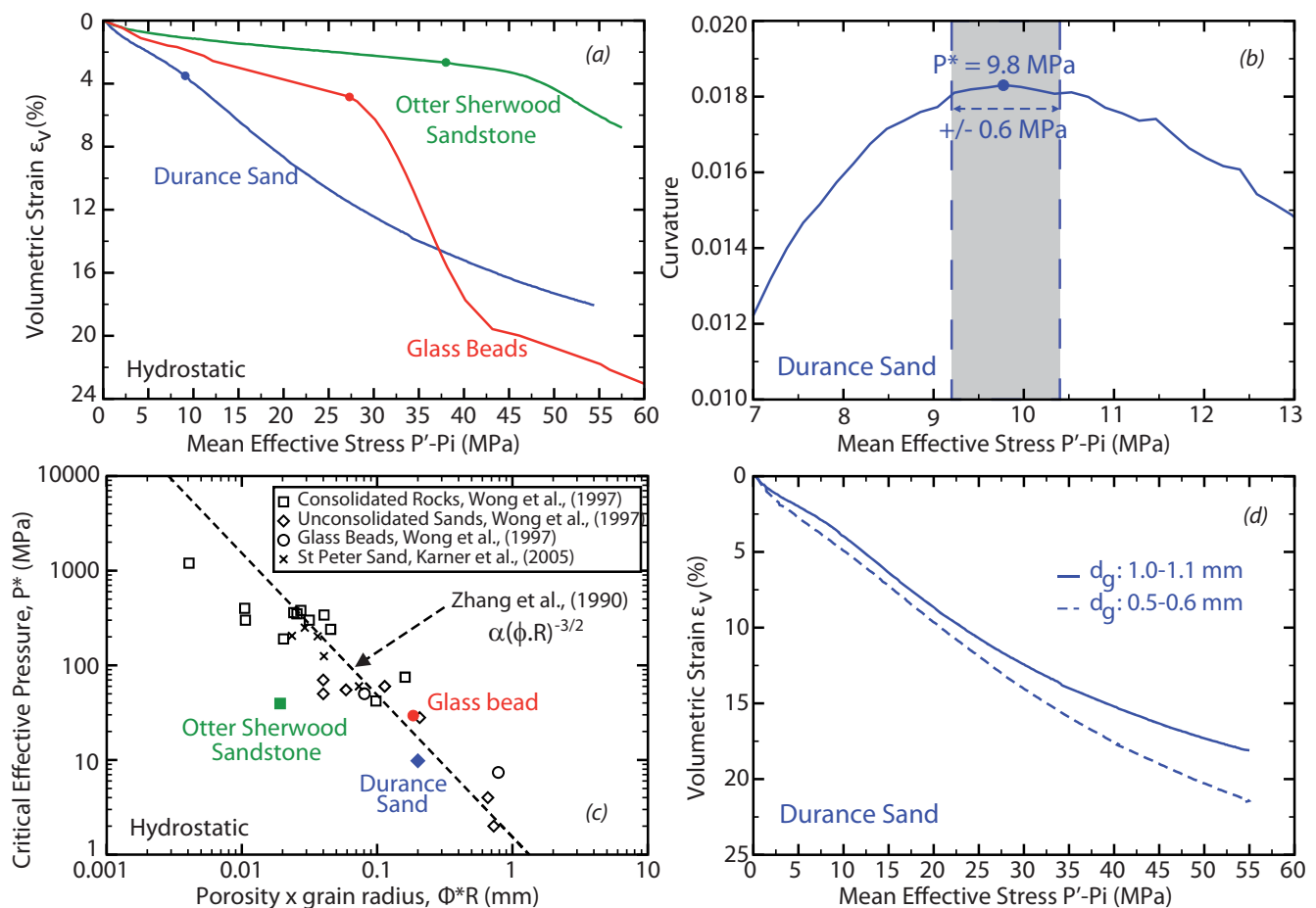


Fig.4. Isotropic compaction tests for three materials (a) ($P_i = 2$ MPa for Otter Sherwood sandstone; $P_i = 3$ MPa for glass beads, and $P_i = 0.7$ MPa for Durance sand), comparison with Wong et al.'s results (b), curvature calculation example (c), isotropic compaction tests for two type of grain size of Durance's sand (d)

extraction (thanks to former brine saturation, salt deposit at grains contact consolidated sufficiently the sand), analysis of damage was performed. First, evolutions of grain size distributions by PLD were performed (Fig.5a, b). Grain damage has clearly occurred for both unconsolidated materials as shown by the flattening of the distribution peak at $d_g = 1$ mm (frequency decreased by a factor 2) and the development of a tail towards small particles sizes down to $100\mu\text{m}$ and less. Yet it also means that not all particles were broken and that some of them may only be cracked or even undamaged. Part of macroscopic samples were then saturated with epoxy resin and miniplugs of 10mm diameter were cored and imaged by X-ray micro-tomography with a pixel size of $\sim 10\mu\text{m}$. Fig.5a, b shows the μ -CT images of the compacted glass beads and Durance sand; in both case, the authors observe Hertzian fracture radiating from some grain contacts, fine particles aggregates resulting from complete grain crushing and some undamaged grains. These observations are in agreement with the grain sizes distribution of compacted samples. Durance sand shows a more homogeneous distribution of cracked

and crushed particles while glass beads present clusters of undamaged particles surrounded by a connected network of crushed material, which geometry reminds force chains network as shown in numerical simulations. This observation might explain the difference of mechanical behaviour between the sand and glass beads.

- Sandstone: Grain size distributions were also measured by PLD (Fig.5c) on Otter Sherwood sandstone. Distribution peak decreases by 30%, the distribution tail is broader and sub-micron particles appear. To observe damage of this complex mineralogical sandstone, SEM imaging on thin sections was performed (Fig.6). The authors observe fractures propagating through grain contacts and zone of crushed material; these features are observed equally in quartz and feldspar grains. Indentation of feldspar by quartz grains is also observed, but such deformation pattern pre-exists in the undeformed material. As for the unconsolidated material, few undamaged grains are also present; the mica present strong plastic deformation; as these minerals are softer, they are com-

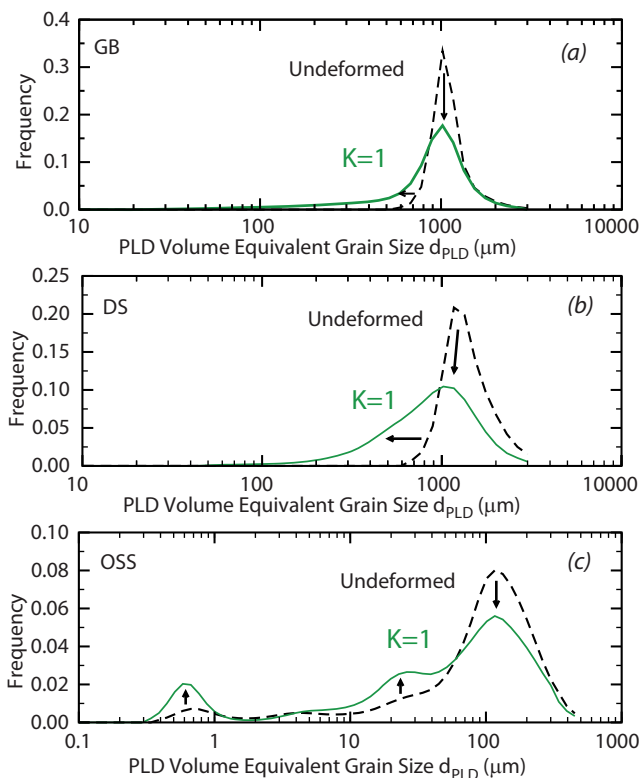


Fig.5. Grain size distribution; glass beads (a), Durance sand (b), Otter Sherwood sandstone (c)

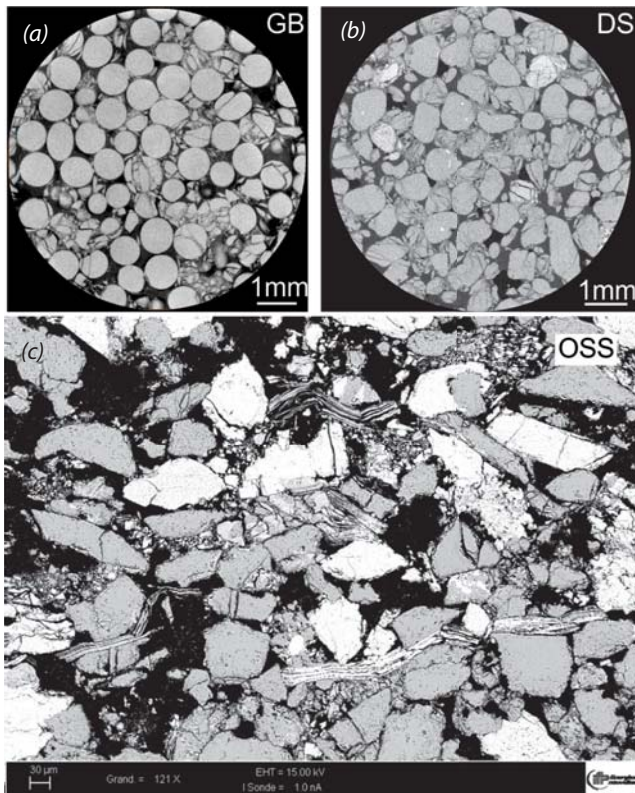


Fig.6. Observations of damaged samples after isotropic compression tests: using micro-tomography on small plugs of (a) glass beads and (b) Durance sand and (c) SEM on polished section of Otter Sherwood sandstone (perpendicular to the bedding plane)

pressed and strongly deformed to accommodate the local movements of quartz and feldspar grains. Inelastic deformation of mica mineral is expected to occur at lower stress and may contribute to early plastic deformation, but the overall mechanical behaviour should be dominated by the major minerals. Some of these observations on Otter Sherwood sandstone are similar with the one of Zhang et. [10] on the weakly consolidated Boise sandstone.

3.2. Compaction tests with different stress paths

3.2.1. Experimental procedures

Different stress paths with constant $K = \frac{\Delta\sigma'_h}{\Delta\sigma'_v}$ were investigated in this study in addition to the hydrostatic compression ($K = 1$), in order to fully characterise the hydromechanical behaviour of the tested materials, where $\Delta\sigma'_h$ represents the change in radial effective stress and $\Delta\sigma'_v$ the change in axial effective stress (Fig.7). Two types of tests were performed:

- Drained proportional triaxial stress path with constant $K = [0.0; 0.2; 0.3; 0.4; 0.6; 0.8]$;
- Undrained triaxial compression at different confining pressures (only for the sand).

In order to be able to compare all our experiments, the authors run all the tests with the same axial loading rate $\dot{\sigma}_a = 0.1 \text{ MPa} \cdot \text{min}^{-1}$.

3.2.2. Results

Different deviatoric compression tests following stress-paths of $K=0.0; 0.2; 0.3; 0.4; 0.6$ and 0.8 were performed on Durance sand and Otter Sherwood sandstone. The

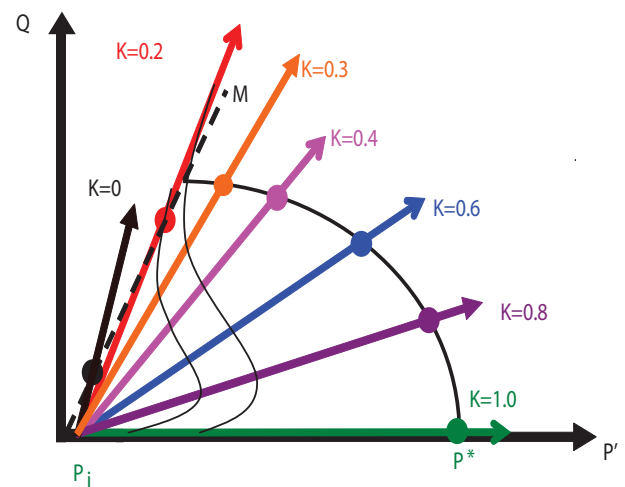


Fig.7. Stress path tested to characterise the hydromechanical of material: triaxial ($K = 0$) and proportional triaxial ($K > 0$) compression tests

evolution of strains (axial, radial, volumetric and deviatoric) with mean effective stress is shown in the Fig.8. As radial extensometer was unavailable during permeability measurements of oil saturated sand, deformations measured for dry sand are presented instead.

First the authors observe an initial compaction regime up to 2.5MPa (except $K = 0.2$) for Durance sand and 10MPa for Otter Sherwood sandstone. This is due to a rearrangement of sand grains towards tighter packing and the closure of voids at the microstructure scale (pre-existing micro-fissures, relaxed contacts) in the weakly consolidated sandstone.

Then in the “elastic” deformation regime, the authors observe for the sandstone that the evolution of volumetric strain is similar for all proportional triaxial stress paths and that the behaviour is strictly compactant; for $K = 0$, the elastic deformation regime has not been reached when

inelasticity starts. For the sand, a linear elastic evolution is difficult to identify and the evolution towards the inelastic regime is widely spread and controlled by the stress path. We observe that the stress path parameter K , showing the deformation behaviour comparable to a uniaxial strain condition (i.e. zero radial deformation) ranges in the interval $[0.4; 0.6]$ for the sandstone and $[0.2; 0.4]$. This condition is commonly assumed as an approximation of the actual stress path followed by a reservoir, assuming one-dimensional compaction associated with fluid pressure depletion [6].

The transition from elastic to inelastic regime is sharper for the sandstone than for the sand at any value of K , and for each material the transition becomes smoother for increasing value of K . When exiting the elastic deformation regime, while the axial deformation is strictly compactant, the radial deformation evolution

reverses for stress paths $K \leq 0.4$ for the sand and $K < 0.6$ for the sandstone; yet the volumetric behaviour remains purely compactant except for the smaller stress paths, respectively $K = 0.2$ and $K = 0$. To pick up the location of the transition (yield stress), similar criteria have been used as for the hydrostatic test, i.e. maximum curvature of stress-volumetric strain curve for the sand and departure of linearity for the sandstone. The yield stress reduces when the stress path is more deviatoric (magnitude of K reduces); beyond the yield stress, the authors observe more hardening for increasing values of K .

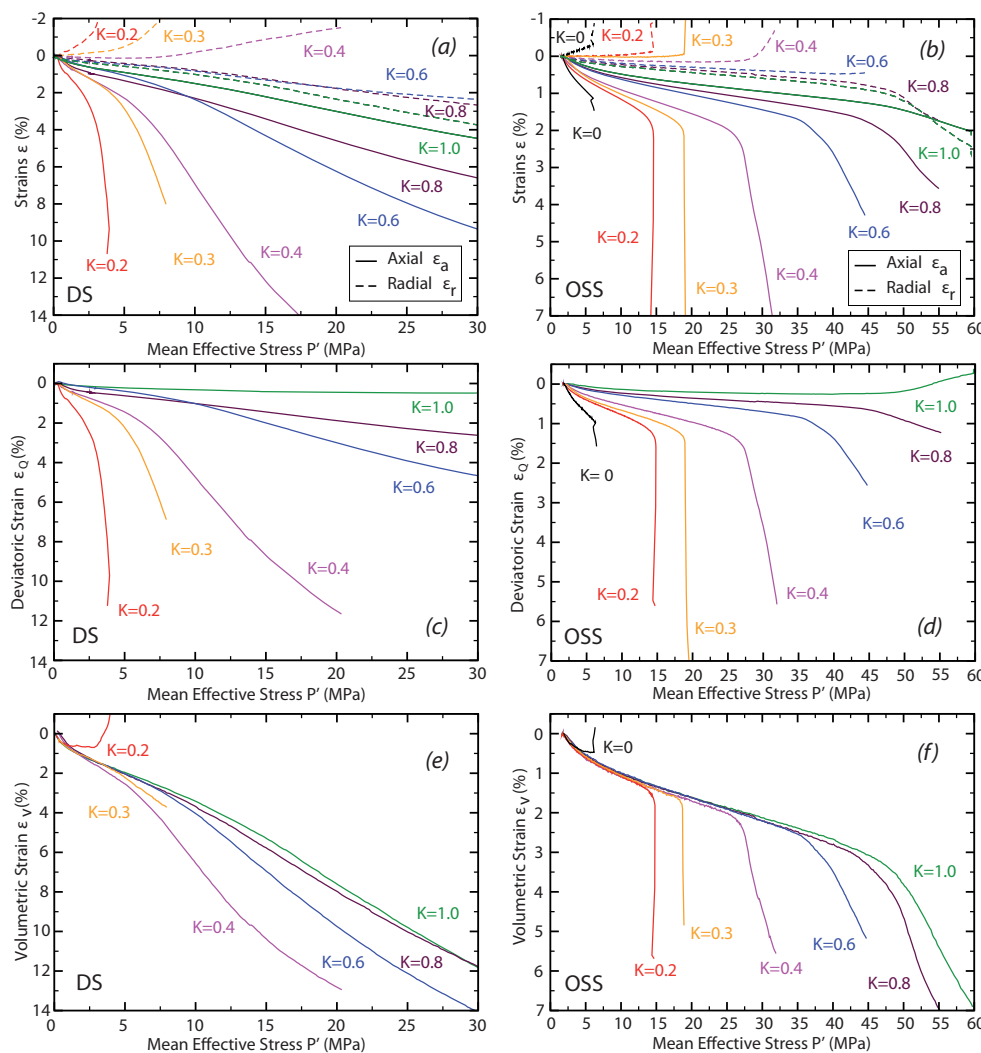


Fig.8. Stress path dependent strain of Durance's sand saturated by brine, (a, b) axial and radial strain, (c, d) deviatoric strain, (e, f) volumetric strain

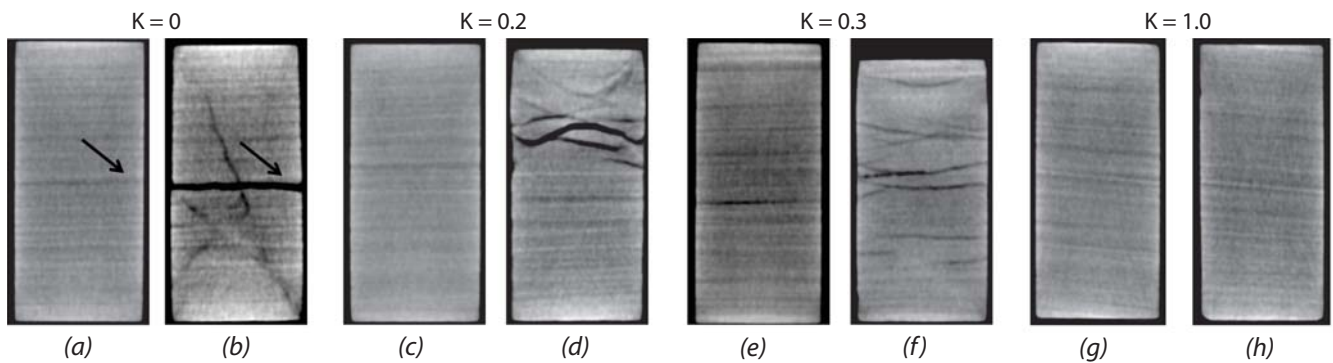


Fig.9. X-ray tomography of samples Otter Sherwood sandstone ($K = 0$), ($K = 0.2$), ($K = 0.3$) and Otter Sherwood sandstone ($K = 1.0$) before and after compaction (a, b), (c, d), (e, f) and (g, h) respectively, with the resolution of 1mm.

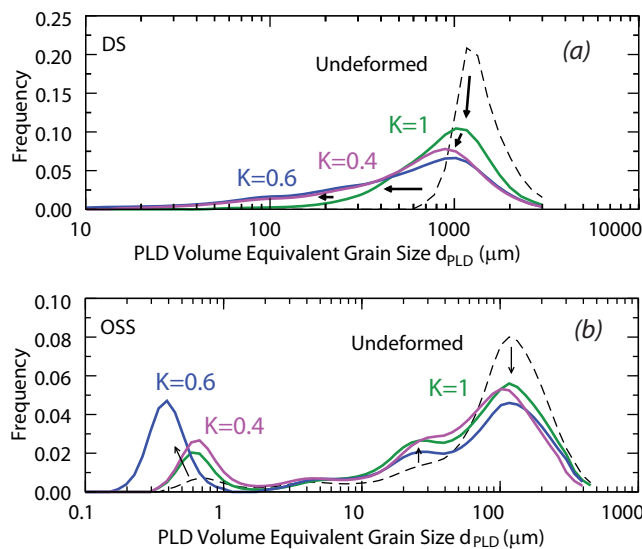


Fig.10. Grain size distribution; Durance sand (a), Otter Sherwood sandstone (b)

of 1mm and a resolution of 400 μ m. For $K = 0$ (Fig.9a, b), an oblique fracture is clearly observed showing the brittle behaviour of the material at low K (the horizontal "fracture" is the result of sample removal from the pressure vessel, corresponding to the location of a low density lamination acting as a weakness plane). For $K = 0.2$ (Fig.9c, d) and $K = 0.3$ (Fig.9e, f) the development of conjugate shear bands in the upper part of the sample shows the complex transitional regime between the brittle and cataclastic behaviour of material. For all $K \geq 0.4$, the CT-scans resolution is not sufficient to identify any localisation of the deformation (Fig.9g, h). For the sand samples, it is difficult with our set-up to extract representative sample out of the sleeve to observe localisation pattern of deformation.

Fig.10 shows the particle size distribution between the undeformed materials and the deformed samples under the deviatoric stress paths $K = 0.4$ and $K = 0.6$. As the stress path becomes more deviatoric, the compression produces more particle damage, highlighted by a more pronounced tail of particle size distribution for the sand and the enhancement

of the second peak in the sub-micron range. In order to get better knowledge of damage mechanisms for deviatoric stress paths, a microstructural study using thin-section analysis and microtomography is currently under way.

3.3. Yield surface

Basically, both unconsolidated and weakly consolidated sands display an elasto-plastic behaviour during depletion [13; 34]. Four constituents are required for fully describing the elastoplastic material response, which are obtained from experimental measurements [17; 18; 19; 35]: elastic parameters, yield surface, plastic potential and hardening parameter. Laboratory stress path testing is useful to map out combinations of yield surface shape for a given geomaterial. Changes of stress inside the current yield surface correspond essentially to recoverable deformation.

The "modified Cam-clay" elastoplastic model in Wood [18] consists in a yield function bounding this region of elastically attainable combinations of effective stress; it is given by:

$$f(P', Q, P^*) = Q^2 + M^2 P' (P' - P^*) \quad (\text{Eq.4})$$

Where P' and Q are the mean effective stress and the differential stress respectively, the parameter $M = (6 \sin \phi) / (3 - \sin \phi)$ is a material parameter related to the Mohr-Coulomb friction angle ϕ , controlling the shape of the ellipse and P^* is the consolidation pressure controlling the size of the ellipse and corresponding physically to the "memory" of the material. M corresponds also to the slope of the critical state line.

A different approach was proposed by Wong et al. [3] who claim on the basis of triaxial experiments on various sandstones that the following normalised elliptic equation holds for the yield surface:

$$((P'/P^* - \gamma)^2 / (1 - \gamma)^2) + ((Q/P^*)^2 / \delta^2) = 1 \quad (\text{Eq.5})$$

Where P^* is the critical pressure at the onset of grain

crushing under hydrostatic loading; γ and δ are parameters of the model.

As shown in the section 3.1 and 3.2, the "elastic" domain of materials is determined by the yield stresses corresponding to the different stress paths. For the Otter Sherwood sandstone, the yield stress is defined as often

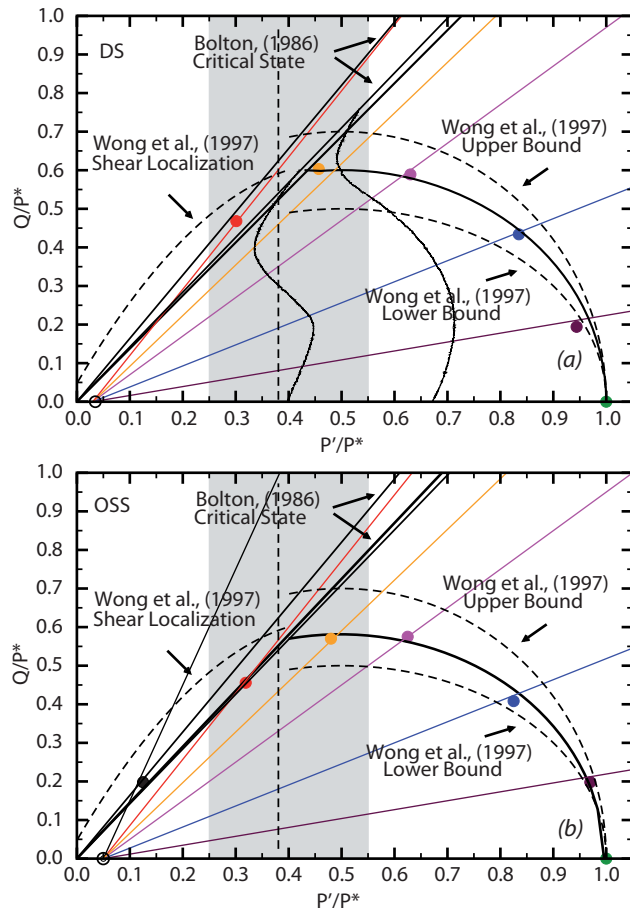


Fig.11. Normalised yield caps; Durance sand (a), Otter Sherwood sandstone (b)

as the onset of irreversible plastic strain. For the Durance sand, the relationship between strain and stress is non-linear and the onset of inelasticity cannot be picked; thus the authors used the criteria of maximum curvature to define the yield point [28]. By using those two definitions, adapted to the different behaviour of the sandstone and the sand, the authors obtained the yield surface for each material in the P' - Q stress space.

In Fig.11, Tables 5 and 6, all yield stresses are normalised to the yield stress under hydrostatic condition, i.e. the critical pressure P^* for each material. It appears that Durance sand and Sherwood sandstone have similar yield surfaces and can well be modeled as elliptical caps. Indeed, our experimental data perfectly match within the bounds defined by Wong et al. [3] in the normalised stress space. These boundaries have been determined from a compilation on experimental results on 6 sandstones with porosities ranging from 14.5 to 35%, tested in triaxial conditions. In addition, the data corresponding to brittle shear failure is included between the two critical state lines defined by Bolton et al. [36]. Our results are also in accordance with those obtained by Crawford et al. [13] for three unconsolidated sands with porosities in the range from 34.3 to 37.5%. As shown in Fig.11, a relative uncertainty remains on the definition of the boundary of elastic and plastic regimes, which can be reduced by performing such tests in the range $0.2 < K < 0.4$.

According to equations (4) and (5) and the yield stresses plot in Fig.11 the parameters of the yield envelopes are the following:

- For the modified Cam-Clay model, best fits give ($M = 1.1$; $P^* = 10\text{MPa}$) for Durance sand and ($M = 1.2$; $P^* = 40\text{MPa}$) for Otter Sherwood sandstone.

Table 5. Durance sand

Samples	Stress Path K	σ'_a (MPa)	P'_c (MPa)	P' (MPa)	Q (MPa)	P'/P^*	Q/P^*	ΔP^* (MPa)
DS (D)	1.0	9.8	9.8	9.8	0.0	1.0	0.0	0.60
DS (D)	0.8	10.8	8.8	9.5	2.0	0.97	0.20	0.50
DS (D)	0.6	10.9	6.7	8.1	4.2	0.83	0.43	0.60
DS (D)	0.4	10.0	4.3	6.17	5.7	0.63	0.58	0.35
DS (D)	0.3	8.3	2.5	4.40	5.8	0.45	0.60	0.06
DS (D)	0.2	6.02	1.42	2.95	4.6	0.3	0.47	0.01

Table 6. Otter Sherwood sandstone

Samples	Stress Path K	σ'_a (MPa)	P'_c (MPa)	P' (MPa)	Q (MPa)	P'/P^*	Q/P^*
OSS V (W)	1.0	39.5	39.5	39.5	0.0	1.0	0.0
OSS V (W)	0.8	43.2	35.4	38.0	7.8	0.96	0.20
OSS V (W)	0.6	43.4	27.1	32.5	16.3	0.82	0.41
OSS V (W)	0.4	39.6	16.6	24.2	23.0	0.62	0.57
OSS V (W)	0.3	32.46	10.02	17.5	22.44	0.44	0.56
OSS V (W)	0.2	24.4	6.2	12.2	18.2	0.32	0.46
OSS V (W)	0	9.8	1.9	4.5	7.9	0.13	0.20

- For the Wong et al. model, best fits give ($P^* = 10\text{MPa}$, $\gamma = 0.5$, $\delta = 0.55$) for Durance sand and ($P^* = 40\text{MPa}$, $\gamma = 0.5$, $\delta = 0.55$) for Otter Sherwood sandstone.

3.4. Stress dependent permeability

Before each loading, the vertical permeability is measured at the initial hydrostatic pressure (3MPa for the sand and 2MPa for the sandstone) using the standard steady state method; several successive flow rates are applied between the inlet and the outlet of the sample and the resulting differential pressures are measured by dedicated sensors. Then while loading, the permeability is measured continuously using a single flow rate and by taking into account the deformation of the sample. Finally, the permeability is determined using the steady state method as described above, at maximum stress (when dP stability allows it) and at the hydrostatic unloaded state. Multi-flow rates permeability is used as quality control of the single flow rate continuous measurement, less accurate.

3.4.1. Hydro-mechanical end effects (HMEE)

It has been shown in previous works [8, 27] that one has to worry about HMEE when measuring permeability in the axial direction on core samples under stress.

The authors illustrate this point on the Otter Sherwood sandstone experiments; and have plotted in Fig.12 the evolution of vertical permeability of Otter Sherwood sandstone measured simultaneously on the total length ($k_{v,T}$) and on the mid-length ($k_{v,M}$) for two stress paths,

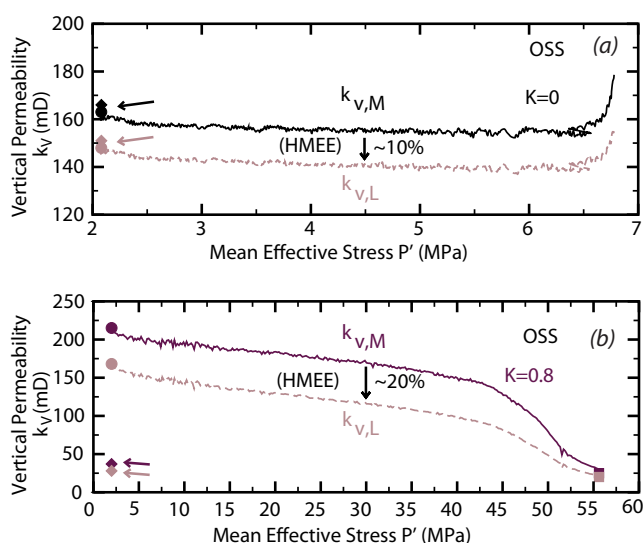


Fig.12. Examples of HMEE on vertical permeability measurements: (a, b) intermediate measurements, unaffected by HMEE, show 10 to 30% of permeability gain compared to classical measurements

one showing dilatancy, $K = 0$ (Fig.12b) and one showing compaction, $K=0.8$ (Fig.12a). In both cases the permeability is obtained from Darcy's law with the assumption that the entire core cross sectional area contributes equally to the flow. The authors observe that the mid-length permeability is systematically higher than the total length permeability in the range 10 to 30% (Table 4). Such discrepancy has also been observed by Gland et al. [8] on Fontainebleau and Bentheimer sandstones and on Estailades Limestone and by Korsnes et al. [27] on Alborg chalk. This effect of pressure drop increase is attributed to the HMEE in the vicinity of the rock/piston interface; it is significant and should thus be taken into account in all studies involving permeability measurements. Despite the discrepancy in absolute values, the authors observe here that the relative variations of both permeability measurements with stresses are in fact comparable whatever the stress-path, meaning that stress dependent permeability evolution measured classically on the full length should still hold on similar weakly consolidated materials. As discussed previously the full-length permeability was not measured on the Durance sand; the experiment additional pressure drops were too important (due to high viscosity of oil) to be compared to the pressure drop inside the too permeable sand. Thus, no HMEE quantification is available for the sand.

3.4.5. Vertical permeability evolution

The authors present for both sands the evolution of mid-length permeability $k_{v,M}$ measured using during compaction under different stress paths, shown in Fig.13. The authors observe that the vertical permeability evolutions of the sandstone follow closely the volumetric deformation evolutions Fig.8 but for the sand, it is not that straightforward. For both material and almost all stress paths, the compression induces significant to drastic permeability reduction associated to compaction, except for the stress path $K = 0$ of Otter Sherwood sandstone where dilatancy is associated with permeability increase.

- Sands: For the Durance sand, the permeability evolution shows also a kind of linear decrease in the "initial" deformation regime but the permeability reduction is much stronger $\sim 0.06.\text{MPa}^{-1}$. In the "plastic" regime, the transition is smooth and permeability reduction softens for all stress path with a delay for more deviatoric ones. Up to final mean effective stress, compaction induces permeability reduction of several orders of magnitude.

- Sandstone: For the Otter Sherwood sandstone, the permeability evolution shows firstly a linear decrease in

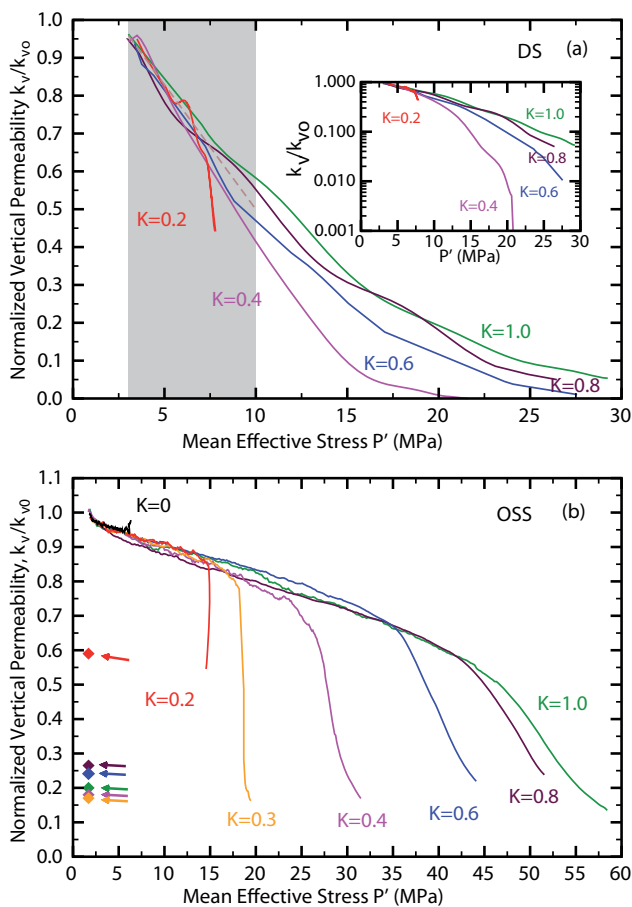


Fig.13. Stress path dependent permeability evolution of: Durance sand (a), Otter Sherwood sandstone (b)

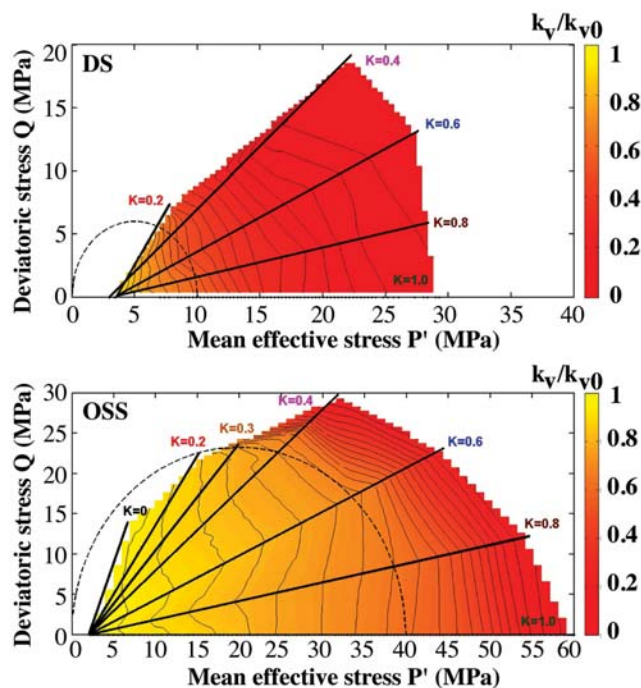


Fig.14. Vertical permeability contours mapped in the P' - Q stress space with experimental stress paths (black lines) and yield cap (dashed line) for Durance sand (a) and Otter Sherwood sandstone (b)

the “elastic” deformation regime followed by a sharper drop in the “plastic” regime. The change of regime is very clear; the initial linear permeability reduction is ~ 0.01 MPa $^{-1}$. Above the yield point, the permeability reduction deviates from linearity and drops drastically. As stress anisotropy increases, permeability reduction is steeper due to shear enhanced compaction. Up to final mean effective stress, compaction induces permeability reduction down to a factor 10.

Thus the stress induced permeability reduction can be highly significant in unconsolidated sands with a lower stress.

By comparing global strains and permeability reduction on Otter Sherwood sandstone, it seems possible to calculate permeability evolution from strains in both regimes; but for angular sand such as Durance sand, a direct relation is not straightforward.

The normalised vertical permeability evolutions are plotted in the (P' , Q) stresses space from which iso-permeability contours are calculated by interpolation of the experimental data Fig.14. This mapping of permeability clearly highlights the fact that the permeability evolution is mainly controlled by the mean effective stress for all stress paths (iso-curves nearly vertical) up to the onset of inelasticity regime where the deviatoric stress starts to influence the permeability reduction (concavity of iso-curves). The permeability reduction rate is firstly a function of mean effective stress and later a function of stress path parameter as well.

5. Conclusions

Our data set from hydrostatic and triaxial stress paths experiments on unconsolidated and weakly consolidated sands can be helpful in understanding the hydromechanical behaviour of such materials. The compaction of this type of materials which is of particular interest to petroleum engineers will be controlled predominantly by how close the in situ stresses are to the yield envelope: the authors plan in a future work to compare the results of the present study to actual reservoir settings. The results of this study on the hydromechanical behaviour of unconsolidated and weakly consolidated sands can be summarised as follows:

- The critical pressure P^* can be predicted by formula of Zhang et al. [10]. However it is over-prediction for the natural material. For sand, the yield stress should be defined at the point of maximum curvature of strain - stress as proposition of Mesri and Vardhanabhuti [28]. For sandstone weakly consolidated, the yield stress can be

used at the end of linear of the curves stress - strain.

- Pressure-induced deformation in quartz, feldspar, mica. The Hertzian fracture was observed in quartz, cleavage surfaces in feldspar and strong deformation plastic in mica.

- Behaviour of weakly consolidated: for deviatoric stress path ($K < 1$), the volumetric deformation curves coincide with the traditional "hydrostatic loading" ($K = 1$) in the initial and second phase of compaction; the proportional stress path reproducing best the uniaxial strain condition stands between $0.2 < K < 0.6$.

- In the inelastic deformation regime, the volumetric behaviour remains purely compactant for all stress paths in investigated, except for $K = 0$ (weakly consolidated) and for $K = 0.2$ (sand) showing brittle behaviour with fracture localisation in weakly consolidated sand; the transition regime is a function of the stress path, smooth at high K and sharp at low K .

- Yield stresses decrease as the stress path becomes more deviatoric and both the modified Cam-clay model and the elliptical cap model capture the onset of plasticity.

- Evolution of yield surface after the hydrostatic preloading was fully justified for sand.

- HME may lead to erroneous measurement of absolute permeability by 10 to 30%, and appear to be insensitive to compaction.

- Permeability evolution follows very closely the volumetric deformation evolution (except $K = 0.2$) and the compression induces a significant permeability reduction associated to compaction, except for the stress path $K = 0$. Iso-permeability contours in $P' : Q$ stress space match roughly the shape of the yield cap.

- Millimetric X-ray scanner resolution is not sufficient to characterise the damage process and localisation for stress path $K > 0$; micro-structural analysis and micro-tomography imaging will help to link the mechanical and permeability evolutions.

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IDENTIFYING THE SOURCES OF PRODUCED WATER IN THE OIL FIELD BY ISOTOPIC TECHNIQUES

Nguyen Minh Quy¹, Le Thi Thu Huong¹, Hoang Long¹, Vo Thi Tuong Hanh²

¹Vietnam Petroleum Institute

²Hanoi Irradiation Centre, Vietnam Atomic Energy Institute

Email: huonglt@vpi.pvn.vn

Summary

The sole objective of this study is to determine the location of formation water aquifer and its flowpath into the Su Tu Den South West basement reservoir. The solution for this study is strongly dependent on the expectation that formation water has been discharged into the aquifer for a certain long time (in the sense of geologic time), so that water-rock interaction has taken place for a period long enough to approach isotope equilibrium ($^{87}\text{Sr}/^{86}\text{Sr}$ as the most important indicator) between formation water and aquifer host rocks. Clastic sediment rocks usually have well-recognised pattern of $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratio in leachates or calcareous minerals according to Strontium Isotope Stratigraphy (SIS), while igneous rocks contain minerals which usually have distinct Sr content and isotope ratio related to mineral type and age of rocks. Therefore, understanding the primeval nature of water before discharging into aquifer by chemical and isotope signatures, in combination with tracing water-rock interaction by isotope equilibrium comparison, can help finding the necessary clues to achieve the study objective.

This data report presents all the analytical results, extracting the primeval signatures of Lower Miocene formation water and basement reservoir water, as well as confirmation for the $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratio equilibrium between Lower Miocene formation water and clastic rocks of Lower Miocene reservoir. The obtained results have assured the method applicability; and it should be recommended to continue the further lab works of environmental isotope analysis as proposed, to identify where the formation water of Su Tu Den South West basement reservoir comes from and the information about its flow path.

Key words: Water stable isotope composition, strontium isotope ratio, the sources of produced water.

1. Introduction

Deuterium (^2H) and oxygen-18 (^{18}O) are environmental isotopes and they are the constituents of natural water molecules. The deuterium and oxygen-18 in the notation of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ are widely used as the signature in studies of the geochemical evolution, recharge processes and water-rock interaction [1, 2, 3].

Strontium is a minor component in the formation water. It is a reactive soluble cation that readily substitutes for Ca^{2+} in carbonates, sulfates, feldspars and other rock-forming minerals. Strontium participates in water-rock interactions. The element is the ninth most abundant constituent dissolved in seawater, and it behaves geochemically like calcium.

In basement rocks the abundance of ^{87}Sr , a daughter of ^{87}Rb , is directly linked to the geochemistry of potassium. Therefore, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio is usually characterised for the geochemistry and age of rocks. With Oligocene and Miocene sedimentary rocks the ^{87}Sr and ^{86}Sr content in grain matrix is inherited from parent rocks, while the content of ^{87}Sr and ^{86}Sr in the joints and cements (mainly

secondary carbonate) is possibly from the equilibrium with those of formation water.

Formation water discharged into the aquifer for a certain long time (in the sense of geologic time), so that water-rock interaction could take place for a period long enough to achieve isotopic equilibrium among minerals in the formation water and aquifer host rocks. In this case the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio is the most important indicator for the interaction equilibrium. Clastic sediment rocks usually have well-recognised pattern of the $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratio in leachates or calcareous minerals according to Strontium Isotope Stratigraphy (SIS) [4, 5], while igneous rocks contain minerals which usually have distinct Sr content and isotope ratio related to mineral type and age of rocks. The SIS curve characterising for the geologic age of minerals was constructed based on the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in typical marine carbonates. This may be done because the oceanic recycling rate is relatively short (< 1,000 years) compared to the long oceanic residence time of strontium (2 - 4Ma) and no natural fractionation of stable strontium isotope was observed during natural

processes. This property makes the strontium isotopic ratio to be a reliable candidate for tracing strontium origin, for evaluating mixing of groundwater and for studying a state of isotope of equilibrium between groundwater and strontium bearing minerals and rocks.

Understanding the primeval nature of water before discharging into aquifer by isotopic signatures, in combination with tracing water-rock interaction by comparing isotope equilibrium, can help finding the sources of production water in a well field.

The formation waters from the oil production of Su Tu Den South West basement reservoir, due to the low strontium concentration in the potential primeval waters, water-rock interaction may approach isotopic equilibrium with respect to strontium. This process could be identified by comparing the $^{87}\text{Sr}/^{86}\text{Sr}$ values of the primary minerals of the host rock and that of the secondary minerals on the joints, cements and pores with those of the strontium dissolved in the formation water.

The purpose of this study was to identify the sources of produced water in the Su Tu Den South West basement reservoir by using isotopic signatures of produced water ($\delta^2\text{H}$ and $\delta^{18}\text{O}$) and the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of minerals from the fields.

2. Experiments

The isotopic compositions of the produced water were measured on an isotope ratio mass spectrometer, Micro Mass (UK) equipped with an elemental analyser (Eurovector, Italy) to convert water molecules into hydrogen and carbon dioxide suited for the deuterium and oxygen analysis. The water stable isotope compositions are defined by the differences of the deuterium to protium and oxygen-18 to oxygen-16 ratios in a sample from those of the Vienna Standard Mean Ocean Water (VSMOW). These differences were expressed by the notation $\delta^2\text{H}$ and $\delta^{18}\text{O}$ in per mill (‰) as follows:

$$\delta^2\text{H} = \left(\frac{{}^2R_{\text{sample}}}{{}^2R_{\text{std}}} - 1 \right) \times 1,000$$

$$\delta^{18}\text{O} = \left(\frac{{}^{18}R_{\text{sample}}}{{}^{18}R_{\text{std}}} - 1 \right) \times 1,000$$

Where ${}^2R_{\text{sample}}$, ${}^2R_{\text{std}}$, ${}^{18}R_{\text{sample}}$ and ${}^{18}R_{\text{std}}$ are the ratio of deuterium to protium and oxygen-18 to oxygen-16 in sample and in the VSMOW standard, respectively.

The pattern, in which $\delta^{18}\text{O}$ and $\delta^2\text{H}$ deviated from the

Global Meteoric Water Line (GMWL) that was described by an equation as:

$$\delta^2\text{H} = 8 \times \delta^{18}\text{O} + 10\text{‰ VSMOW}$$

The pattern, in which $\delta^{18}\text{O}$ and $\delta^2\text{H}$ are deviated from GMWL, is used to trace geochemical evolution or water-rock interaction that formation water has been involved; and then interpreting the primeval nature of formation water.

The $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratios in formation water and rock cutting samples are measured using the thermal ionisation mass spectrometric (TIMS) method and given directly as atomic mass ratios. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio was analysed for bulk samples of the Su Tu Den basement rock and for both leachates and residues of Oligocene and Miocene sedimentary rocks. The leachates were prepared by dissolution of the sediment with acetic acid according to a standard procedure described elsewhere [7, 8]. Briefly, it was as follows: allow 0.3g sample to leach in 5mL solution of CH_3COOH 4M in a glass tube. The content in the tube was intermittently shaken for 8 hours at the room temperature, then allowed to settle for 16 hours so that the total leaching time was 24 hours. The leachate was separated from the residues by centrifugation. The strontium isotopes ratio in the residues and leachates were determined by the TIMS method as described above.

With this extraction procedure, the leachates are considered to be a solution of the secondary carbonate which mainly constitutes the joints and cements, while the residues being the grain matrix of sediments.

3. Results and discussions

3.1. Analytical results

Tables 1 presents the results of the isotopic composition of produced water from the Lower Miocene and basement reservoirs. Table 2 shows the results of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio in strontium dissolved in produced water of the two above mentioned formations. In Table 2 the chloride concentration in the salinity unit (part per thousand, ppt) in the produced water is also shown. Table 3 presents the ratios of $^{87}\text{Sr}/^{86}\text{Sr}$ in the acetic acid leachates and residues of the Miocene and Oligocene rock cutting minerals.

Isotope and geochemical characterisations of water in the Miocene and basement formation are given in Table 4 and 5, respectively.

Table 1. The ^{18}O and ^2H isotopic composition of water samples taken from the Lower Miocene and basement reservoirs

No.	Reservoir	Well	Acquisition Date	$\delta^{18}\text{O}_{\text{VSMOW}} (\text{‰})$	$\delta^2\text{H}_{\text{VSMOW}} (\text{‰})$
1	Lower Miocene	SD-11P	18 July 2010	-3.03	-24.48
2	Lower Miocene	SD-20P	5 July 2010	-3.18	-23.30
3	Lower Miocene	SD-27P	18 July 2010	-2.85	-23.07
4	Basement	SD-3P	18 July 2010	-3.43	-57.52
5	Basement	SD-4PST	18 July 2010	-4.09	-53.61
6	Basement	SD-5PST	3 July 2010	-4.52	-59.76
7	Basement	SD-6P	3 July 2010	-3.98	-56.30
8	Basement	SD-7P	18 July 2010	-3.79	-57.37
9	Basement	SD-18P	3 July 2010	-3.48	-58.70
10	Basement	SD-19P	3 July 2010	-3.61	-60.07
11	Basement	SD-22P	18-Jul-10	-3.66	-59.92

Table 2. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of strontium dissolved in water in the Lower Miocene and basement reservoirs

No.	Reservoir	Well	Acquisition Date	$^{87}\text{Sr}/^{86}\text{Sr}$	Sr (mg/L)	Chloride (ppt)
1	Lower Miocene	SD-11P	18 July 2010	0.707571	3.39	30.09
2	Lower Miocene	SD-20P	5 July 2010	0.707554	3.27	29.65
3	Lower Miocene	SD-27P	18 July 2010	0.707610	3.02	29.87
4	Basement	SD-3P	18 July 2010	0.706884	9.65	10.19
5	Basement	SD-4PST	18 July 2010	0.706845	10.24	12.42
6	Basement	SD-5PST	3 July 2010	0.706900	8.21	9.43
7	Basement	SD-6P	3 July 2010	0.706833	7.87	19.19
8	Basement	SD-7P	18 July 2010	0.706901	8.67	13.03
9	Basement	SD-18P	3 July 2010	0.706865	7.84	11.48
10	Basement	SD-19P	3 July 2010	0.706839	8.63	10.58
11	Basement	SD-22P	18 July 2010	0.706901	7.38	10.47

Table 3. The $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratio of strontium in the acetic acid leachates and minerals of the Miocene and Oligocene rock cutting samples

Reservoir	Well	Depth (mTVD)	$^{87}\text{Sr}/^{86}\text{Sr}$ (Residue)	$^{87}\text{Sr}/^{86}\text{Sr}$ (Leachate)	Remark
Miocene	SD-26P	1,722	0.7112537	0.7076215	B10/BH Formation
Miocene	SD-26P	1,723	0.7113246	0.7075875	B10/BH Formation
Miocene	SD-26P	1,725	0.7111897	0.7075817	B10/BH Formation
Miocene	SD-27P	1,720	0.7108979	0.7107257	Oil Zone/Miocene Tuff
Miocene	SD-27P	1,721	0.7112812	0.7105179	Oil Zone/Miocene Tuff
Oligocene	SD-4P	2,228	0.7108124	0.7088826	C30
Oligocene	SD-4P	2,237	0.7105152	0.7088822	C30
Oligocene	SD-4P	2,246	0.7114355	0.7091526	C30
Oligocene	SD-1X	2,162	0.7107647	0.7085093	C30
Oligocene	SD-1X	2,171	0.7105561	0.708493	C30

3.2. Primeval sources of the formation waters

The origin of the formation waters in high-temperature deep-geological structure can be distinguished by their geochemical and isotopic compositions. Commonly, water in deep geological structures can be originally recharged from the following major water sources [2, 3].

+ Andesitic water: this source is recycled seawater

which has been subducted in regions with andesitic volcanism or convergent plate volcanism. The $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of this water are about $+ (10 \pm 2)\text{‰}$ and $+ (20 \pm 10)\text{‰}$, respectively, while the chloride concentration is similar to that of the seawater;

+ Juvenile water: this source is water coming from the Earth's mantle or core that has never been a part of the hydrospheric cycle;

Table 4. Characterisations of water in the Miocene formation taken for this study

Well	Acquisition Date	Chloride (ppt)	Bromide (mg/L)	$\delta^{18}\text{O}_{\text{VSMOW}}$ (‰)	$\delta^2\text{H}_{\text{VSMOW}}$ (‰)
SD-10P	25 August 2010	30.17	79.2		
SD-10P	13 October 2010	28.06	70.5		
SD-11P	18 July 2010	30.09		-3.03	-24.48
SD-20P	5 July 2010	29.65		-3.18	-23.30
SD-27P	18 July 2010	29.87		-2.85	-23.07

Table 5. Chloride and isotopic composition of basement water

Well	Acquisition Date	Chloride (ppt)	$\delta^{18}\text{O}_{\text{VSMOW}}$ (‰)	$\delta^2\text{H}_{\text{VSMOW}}$ (‰)
SD-3P	18 July 2010	10.19	-3.43	-57.52
SD-4PST	18 July 2010	12.42	-4.09	-53.61
SD-5PST	3 July 2010	9.43	-4.52	-59.76
SD-6P	3 July 2010	19.19	-3.98	-56.30
SD-7P	18 July 2010	13.03	-3.79	-57.37
SD-18P	3 July 2010	11.48	-3.48	-58.70
SD-19P	3 July 2010	10.58	-3.61	-60.07
SD-22P	18 July 2010	10.47	-3.66	-59.92

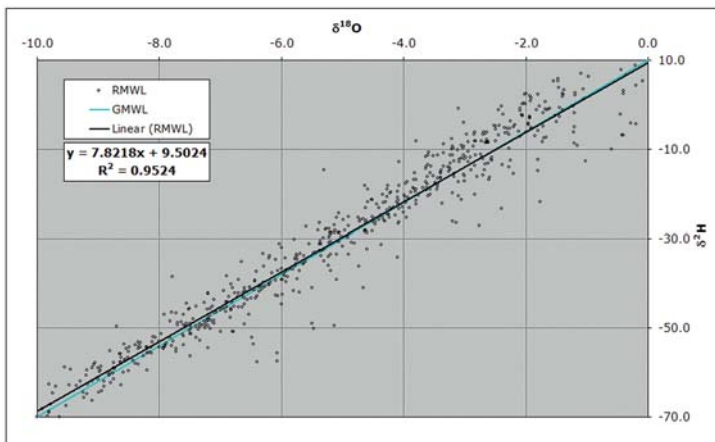


Fig.1. The GMWL ($\delta^2\text{H} = 8\delta^{18}\text{O} + 10$) is plotted with the regional meteoric water line (RMWL: $\delta^2\text{H} = 7.82\delta^{18}\text{O} + 9.50$, black colour line) constructed from observed data around the South East Asian region (dots)

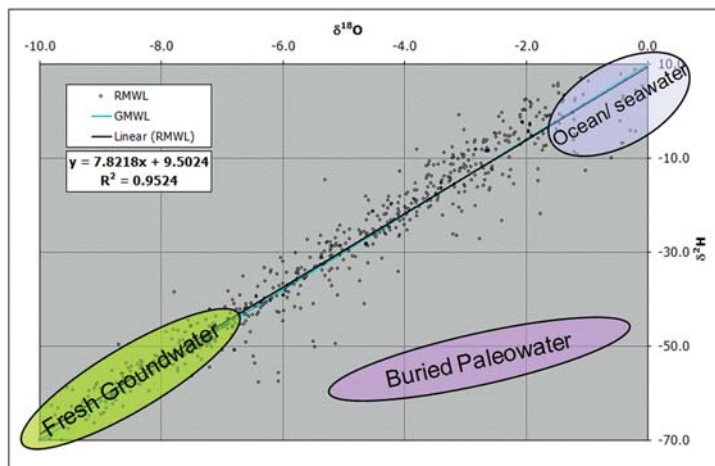


Fig.2. Typical area of fresh groundwater, seawater and paleowater in relation to the global and regional meteoric water line

+ Magmatic water: this source is water that was in equilibrium with magma, regardless of its initial origin. The only separated aqueous phase is magmatic water but not water physically dissolved in the magma;

+ Meteoric water: This water is originated from precipitation and of any age (rain, snow, ice, river water, lake water, groundwater) (Fig.1);

+ Ocean water or seawater: this is water in open oceans which may enter the deep-geological structure.

Andesitic water, juvenile water and magmatic water (sometimes called "tectonic water") are greatly different from seawater and meteoric water. They are easily recognised by the geochemical compositions, e.g. SiO_2 , Ca^{2+} , Mg^{2+} , Ba^{2+} , Li^+ , K^+ , CO_3^{2-} , S^{2-} , Cl^- , F^- , etc. as well as the isotopic composition, i.e. $\delta^{18}\text{O}$ and $\delta^2\text{H}$. The former groups of water usually have high content of solute silica, gases. They are also much enriched with heavy isotopes of water, i.e. the values of $\delta^{18}\text{O}$ are positive ($> +2\text{‰}$) due to the extensive ^{18}O isotope exchange or equilibration with parent rocks.

In this study the waters in the Miocene and basement reservoirs from the Su Tu Den South West basement reservoir are of concerns. From Fig.1 and Table 1 it was revealed that there is no evidence for the occurrence of tectonic water in the Miocene and Basement reservoirs. The primeval nature of the Su Tu Den formation waters might be regarded to as seawater and/or meteoric water because all the $\delta^{18}\text{O}$ values of water in the reservoirs are negative (Table 1). Meteoric water has its $\delta^{18}\text{O}$ and $\delta^2\text{H}$ evolves according to Meteoric Water Line (MWL) and this line has the clear global (GMWL) or regional (RMWL) pattern (Fig.1) [3].

Fig.2 depicts the typical positions of concurrent fresh groundwater, seawater and paleowater in relation to Global and Regional Meteoric Water Lines. In aquifers with fresh groundwater which are locally recharged with recent precipitation, the compositions of the heavy isotopes are commonly similar to the annual mean of these quantities in the rainfall for that area. Therefore, the $\delta^{18}\text{O}$ and $\delta^2\text{H}$ of recent

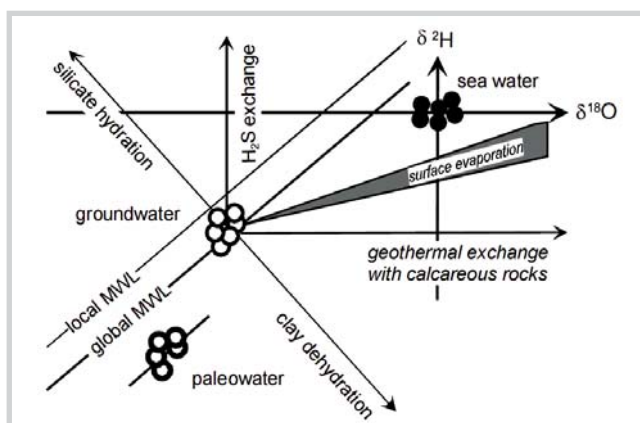


Fig.3. Various water-rock interaction processes which shift the $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values from the MWL (adapted from [3])

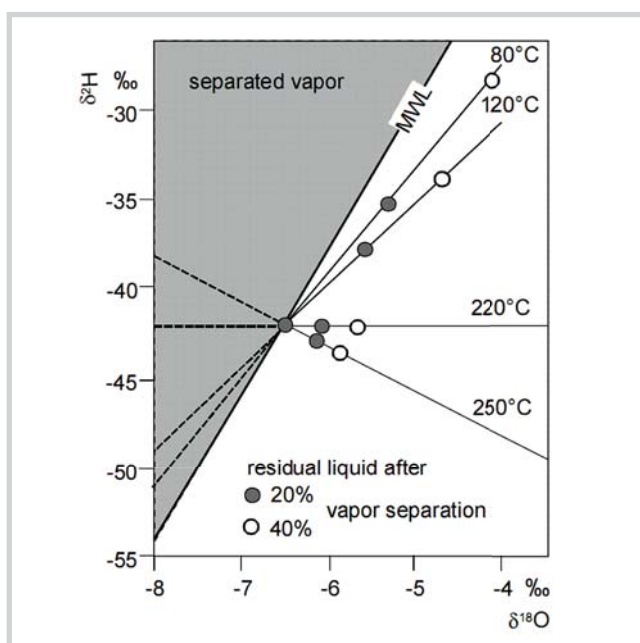


Fig.4. The $\delta^{18}\text{O}$ and $\delta^2\text{H}$ shifted from the MWL due to the steam loss at various high temperatures (adapted from [3])

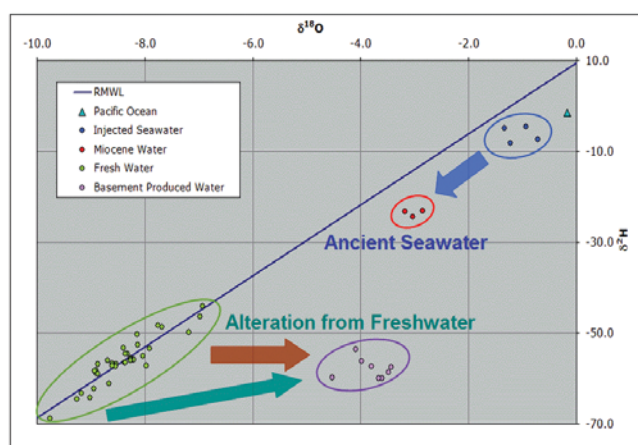


Fig.5. The $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of the waters from the Su Tu Den South West Miocene & basement reservoir and their predicting primeval nature

groundwater are aligning close to the RMWL. The $\delta^{18}\text{O}$ and $\delta^2\text{H}$ of seawater should be clustered around the zero point of the ordinate (by the definition of the notation). Seawater signature is also easily recognised by comparing the Cl, Br concentration with the $\delta^{18}\text{O}$ value.

Paleowater is buried and experienced with long and extensive water-rock interactions or high-temperature steam loss, therefore, its $\delta^{18}\text{O}$ and $\delta^2\text{H}$ is largely shifted from the GMWL or RMWL (Figs.3 and 4).

It can be seen from Table 4, that the chloride of water in the Miocene formation is highly homogenous despite the fact that the waters were sampled from different wells and at greatly different times. These water samples also have a close correlation of chloride and bromide concentration which is higher than that of today seawater (the results are not shown here). In this study, the $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of water in the Miocene formation are positioned below the RMWL but somewhat close to the area of seawater (Fig.5). However, the values of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ are more negative than that in seawater (red dots cluster in Fig.5). With all the mentioned above evidences, it might be suggested that the primeval nature of water in the Miocene formation is ancient seawater.

The $\delta^{18}\text{O}$ and $\delta^2\text{H}$ in produced water from the basement shown in Table 1 and plotted in Fig.5 also indicate a clear pattern of paleo-groundwater (open dots cluster in Fig.5). The $\delta^2\text{H}$ values in the produced water from the basement characterise for fresh water (from -57 to -60‰), while the $\delta^{18}\text{O}$ values are in the range of seawater (around -4‰). However, the chloride of water in the basement is far lower than that of the seawater. It was of 10 - 12ppt versus 30ppt in seawater (Table 1). These signatures clearly indicate that the primeval nature of water in the basement formation is meteoric but the water has undergone the isotope alterations by thermal water-rock interactions (the brown arrow in Fig.5, see also Fig.3) and/or steam separation processes under high temperature (green arrow in Fig.5, see also Fig.4). The conclusion on the primeval meteoric origin of water in the basement formation agrees with the results of our previous study on Su Tu Den South West basement produced water.

3.3. Strontium isotope equilibrium

It can be seen from Table 2 that despite the fact that water samples were taken from various wells, the

$^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratios of strontium dissolved in water of the basement formation are all close to each other being around 0.7068 - 0.7069. Three Miocene formation water samples have close $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratios of around 0.7075 - 0.7076 (Table 2). It should be noted that the instrumental precision in the $^{87}\text{Sr}/^{86}\text{Sr}$ analysis must reach 6 decimal numbers as a difference at the 4th decimal number could be a great value accounting for an uncertainty of millions years in the geologic scale. So, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios found for strontium dissolved in water in the Miocene and basement reservoir have distinct $^{87}\text{Sr}/^{86}\text{Sr}$ values indicating the different nature of water in the corresponding formations. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of strontium in the residues of Miocene and Oligocene clastic sediment rocks are in a range of 0.7105 to 0.7113 and higher than that in seawater (Table 3). The strontium isotope ratios found in the residues are largely distinctive from the corresponding quantity in the leachates, ranging from 0.7083 to 0.7107 (Table 3). These differences might be found in the nature of strontium in the two fractions. On the one hand, the residues are inherited from parent rocks having older age and as the consequence the ^{87}Sr contribution from the long-live ^{87}Rb decays should be higher. On the other hand, the residue components, virtually being solid grain matrix, are isolated or have limited possibility to contact with pore fluids, so they might have no interaction with the formation water leading to negligible effects on the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the formation water. Moreover, sediment grains, which remained after long processes of weathering, erosion and transportation from distant parent rocks, are usually chemically stable and inert towards the interaction with intact water. All these made the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the residues higher compared to those in leachates.

The data of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios clearly shows the equilibrium of strontium isotopes between Miocene formation water and the leachates from siltstone of the Miocene B10 sequence. In the previous section, we have concluded on the primeval nature of the Miocene formation water. This primeval water source has its typical strontium behaviour and the predictable fashion of $^{87}\text{Sr}/^{86}\text{Sr}$ ratio. In our previous studies on sedimentary facies it has been indicated that Miocene clastic sediments were formed in marine environments and the formation water, which was discharged in these sediments, is likely at an age of Miocene or later geologic time. Accordingly, the original $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of Miocene

formation seawater can be predicted by lookup from the Strontium Isotope Stratigraphy (SIS) curve [4, 5] and the predicted value should be greater than 0.7082. The $^{87}\text{Sr}/^{86}\text{Sr}$ value found in this study was approximately 0.7076 for the Miocene formation water. Based on the data found and the SIS curve, the formation water in the Miocene would be dated back to the Late Cenozoic to Paleogene age of about 75Ma. It is unlikely to happen because this was an erosion period in the study area. Therefore, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.7075 - 0.7076 in the Miocene formation water are possibly indicated on the controlling of the equilibration with the solid phase in the joints and cements of Miocene clastic sediments which have similar $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of approximately 0.7076 in the leachates.

There are also two samples taken in the top of the Miocene B10 layer of well 27P and described as volcanic tuffs in the petrology analysis report [6] of which their leachates have quite different $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in comparison with those in the leachates from siltstone of Miocene B10 (Table 3). Volcanic tuffs, if really existed at the Miocene B10 top, might be local lens and hardly interact with formation water and contributed to the strontium isotope equilibrium. It is also likely that these samples are unrepresentative for Miocene clastic sediment as perceived by the description in the well 27P petrology report [6].

The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in basement produced water being around 0.7068 - 0.7069 are relatively low and distinct from those in the Miocene and Oligocene cutting rock. These results have excluded Oligocene sediments as the potential host aquifers for basement formation water. Because of that the primeval source of Su Tu Den South West basement formation water was the meteoric. This kind of water originally contains very low concentration of strontium, eg. Sr concentration in river water typically is around 0.6mg/L, and that in circular groundwater is around 1mg/L. However, the Sr concentration found in all the basement water samples was higher than seawater of 8mg/L. These results clearly indicate that strontium concentration in basement water was contributed from the dissolution in host rocks of aquifers or along flowpath. These dissolution processes assure the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio in formation water to be an indicator for those ratios of aquifer host rocks. A broader collection of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio data for possible host rocks can be used to identify the location of the aquifer.

4. Conclusions

Geochemical and isotope ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) compositions are helpful in identifying the primeval nature of Su Tu Den South West reservoir water: Miocene formation water is confirmed to be ancient seawater; Basement formation water is determined as alternated fresh water.

The $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratios analysis have proved the $^{87}\text{Sr}/^{86}\text{Sr}$ isotope equilibrium between formation water and sedimentary rock in Miocene reservoir as proposed.

Basement water samples have high Sr contents (~ 8 - 10mg/L), while their primeval source (freshwater) usually has low Sr content (< 1mg/L). This result indicates Sr contribution from host rocks of the aquifer, so it is favourable for identifying aquifer location by $^{87}\text{Sr}/^{86}\text{Sr}$ isotope analysis. Therefore, further labs works should be continuously conducted.

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OIL AND GAS POTENTIAL OF THE REPUBLIC OF UZBEKISTAN - CURRENT STATUS AND OPPORTUNITY FOR FURTHER DEVELOPMENT

A.N.Bogdanov

Institute of Geology and Exploration of Oil and Gas fields (IGIRNIGM) Tashkent, Republic of Uzbekistan

Email: bogdalex7@yandex.ru

Summary

The analysis of exploration work's results in the Republic of Uzbekistan testifies that the hydrocarbon potential of oil and gas regions in the country is still very high and it is advisable to carry out further searches for oil and gas accumulation. The availability of provable reserves of hydrocarbon of more than 9.5 billion tons of oil equivalent allows increasing volumes of exploration work, and attracting foreign investors to build up resource base of hydrocarbons.

Key words: Hydrocarbon potential, Ustyurt, Bukhara-Khiva, South-West Gissar, Surkhandarya, Fergana, Republic of Uzbekistan.

1. Introduction

The oil and gas industry of Uzbekistan has a history of more than 100 years, commencing at the end of the XIX century, with the first commercial development of oil deposits in the Fergana Valley. Even so in the mid of century, the people discovered natural oil seeps on the surface of current territories of Uzbekistan and used it for different purposes.

In 1904, with the development of drilling activities, the first oil was found in Chimion structure at the depth of 300m. That year also marked the first hydrocarbon field discovery (Chimion) in the Republic of Uzbekistan. After that, oil and gas were also discovered in Surkhandarya, Bukhara-Khiva, and Ustyurt regions.

Currently, there are five oil and gas regions with proven productivity in Uzbekistan - Ustyurt, Bukhara-Khiva, South-West Gissar, Surkhandarya and Fergana regions. Besides that, two potential oil and gas regions have been found - Khorezm and Mid-Syrdarya (Fig.1).

2. Oil and gas potential of the Republic of Uzbekistan

2.1. Ustyurt region

This is the leading region with the largest area of potential land of 113,100km², and covers territories of the Republic of Karakalpakstan. This area is poorly studied compared with other oil and gas regions in Uzbekistan.

Exploration work has been conducted here for almost 50 years. Drilling activity is still limited with averagely one well per 320km² (Fig.2).

The first field Shahpahty (gas) was discovered in 1963. Commercial flow mainly comes from Jurassic deposits, rather than Paleozoic deposits with its main product being gas-condensate. However, no commercial flow of oil and gas shows in deposits of Paleozoic and Jurassic in other areas such as Karakuduk, East Munak, Garbiy Barsakelmes, etc. In 2012, on the Western Aral field, which was discovered in 2010 by the Consortium of Investors (NHC Uzbekneftegaz, Petronas Carigali (Malaysia), Lukoil (Russia), CNPC (China), and KNOC (Korea), the first in the Ustyurt region commercial oil reserves was announced.

For the whole exploration period in the Ustyurt region, 16 oil and gas fields have been discovered with 1 gas field,

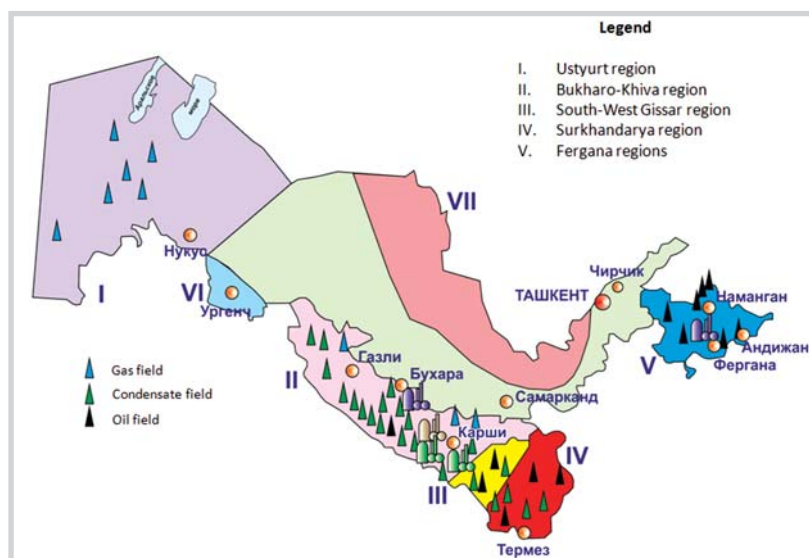


Fig.1. Oil and gas regions in Uzbekistan

1 oil-gas-condensate field and 14 gas-condensate fields. Up to now, 4 fields are in development phase, 5 fields in pre-development or suspension and 7 fields under appraisal.

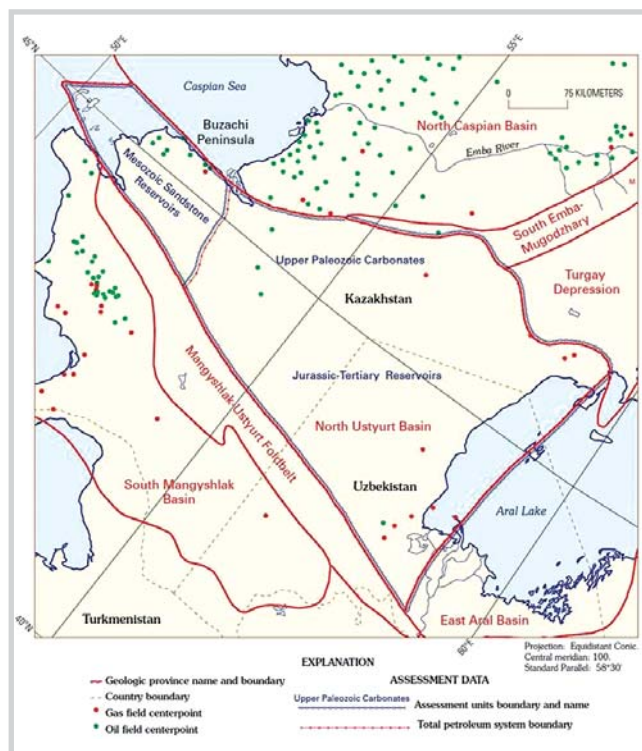


Fig.2. Ustyurt region on the regional geology units

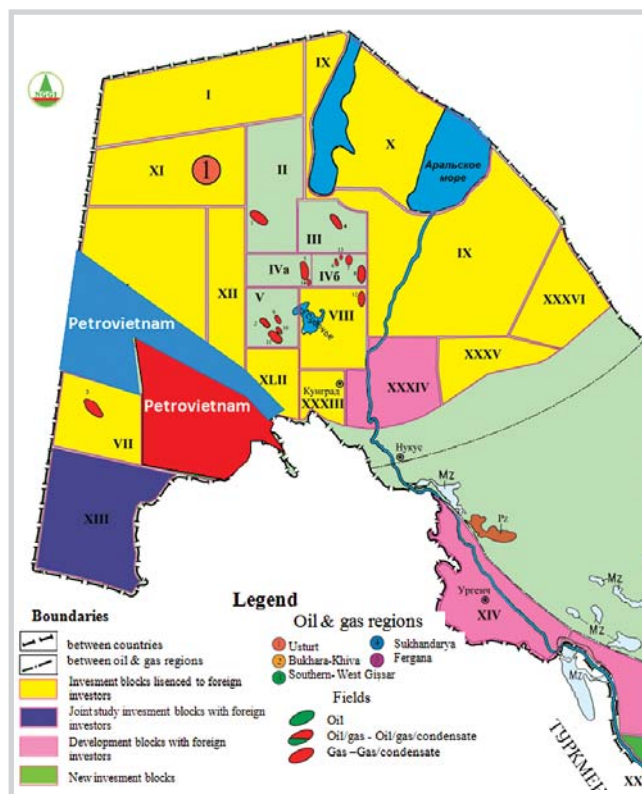


Fig.3. Location of Investment blocks in the Ustyurt region

There are 21 investment blocks allocated within the Ustyurt region. In different periods exploration work and fields development have been performed by various companies like Gazprom Zarubezhneftegaz (Russia), LUKOIL (Russia), Petronas Carigali (Malaysia), CNPC (China), KNOC (Korea), Tethys Petroleum (Great Britain), Daewoo International (Korea), and Petrovietnam (Vietnam) separately.

Explored reserves of the Ustyurt region account for 16.6% of the total explored reserves in Uzbekistan.

Further potential of increasing hydrocarbon reserves in the coming years will be based on deposits of Jurassic and Paleozoic age. Priority should be given to territories of Kosbulak, Kulbay-Atorbay, Sudoch'ye deflections, Kuanysh-Koskalin uplift, Shahpahtin and Uzunkuin steps, the modern basin of Aral Sea and the Eastern and Southern parts of the Aral Sea area, etc.

Apart from deposits of Jurassic age, significant prospects are involved with formations of Paleozoic age. At the present time, these deposits contain two gas-condensate fields, which are Karachalak and Kokchalak, and also hydrocarbon flows in the areas of Central Kushkair, Chibiny, Northern Urga, and Karakuduk, etc.

In addition, certain prospects are connected with the Lower Cretaceous terrigenous deposits of the Ustyurt region in Doris area (territory of Kazakhstan), to the north of the northern border of Karakalpakstan. The high-capacity oil flows are received in sandy collector of Neocom stage of wildcat well № 1.

The total amount of recoverable hydrocarbon resources of the Ustyurt region adds up to around 3.4 billion tons of oil equivalent.

2.2. Bukhara-Khiva region

It is the second largest oil and gas region by area (53,800km²) with established industrial productivity. It covers the territories of Bukhara, Kashkadaria, Samarkand and Navoi areas. Exploration work has been conducted here for more than 60 years. The drilling density is about 1 well per 25.0km².

The first field Setalantepe (gas) was discovered in 1953. Commercial flows in Bukhara-Khiva region mainly come from Jurassic and Cretaceous age. In addition, some non-commercially unimportant oil shows were marked in deposits of Paleozoic age in separate areas and fields (Northern Mubarek, Shurchy, and Karaulbazar-Sarytash, etc.).

Throughout the exploration periods, 163 oil and gas fields have been discovered in the Bukhara-Khiva region with 6 gas fields, 52 oil-gas-condensate fields, 18 oil fields and 87 gas-condensate fields. Up to now, 66 fields are in development phase, 60 fields in pre-development or suspension and 37 fields under appraisal (Fig.4).

There are 12 investment blocks within the Bukhara-Khiva region. At different periods, exploration work and fields development have been performed by various companies like LUKOIL (Russia), CNPC (China), Tethys Petroleum (Great Britain), Uzmal Oil (Malaysia), UzGazOil, Gissarneftegaz (Switzerland), and Petrovietnam (Vietnam).

The Bukhara-Khiva region possesses 65,8% of the total explored reserves of the Republic of Uzbekistan.

The further prospects of increasing hydrocarbon reserves in this area focus on the Chardzhou step where major oil and gas discoveries were mainly made in the Jurassic carbonate. This is also the main and important target of exploration in the near future (Fig.5).

Among the priorities for exploration work, it is possible to define the territories of the Beshkent macro deflection, the northwestern part of the Chardzhou step (within the Gugurtli uplift and in frontier zone in the South, between Kandym and Dengizkul - Zevardin uplift) of Kashkadaria deflection. The western part of the Mubarek uplift section between Karaktai - Karakum fields, is the most potential. The southern part of the Kagansk uplift, along the grading fault of Bukhara - Chardzhou steps and Sarytash - Yulduzkak area, is the potential area for exploration plan in the future.

Besides carbonate deposits of Middle-Upper Jurassic age, certain prospects are connected with terrigenous deposits of Lower-Middle Jurassic and Lower Cretaceous ages.

Furthermore, hydrocarbon potential also exists in Paleozoic formations.

The total amount of provable recoverable resources of hydrocarbon in the Bukhara-Khiva region adds up to 3.2 billion tons of oil equivalent.

2.3. South-West Gissar region

The area of potential lands is 5,300km² and covers a part of the territory of the Kashkadaria area. Exploration work has been conducted here for more than 50 years. The average drilling density of the territory is about one well per 25.0km².

The first field Adamtash (gas-condensate) was discovered in 1962. Commercial flows in the territory of the South-West Gissar region mainly come from carbonate deposits of Middle-Upper Jurassic age.

In the South-West Gissar region, so far 19 oil and gas fields have been discovered with 1 gas field, 1 oil-gas-condensate field, 3 oil fields and 14 gas-condensate fields. From the total numbers of discovered fields, 4 fields are in development phase, 5 fields in pre-development or suspension and 10 fields in appraisal process.

There are 3 investment blocks in the South-West Gissar region. In one of them (Gissar) exploration work and field development are being performed by LUKOIL (Russia).

The explored reserves in the South-West Gissar region account for 6.0% of the total reserves of the Republic of Uzbekistan.

Among the priorities for exploration work, it is possible to define the territories of the Akkayrak deflection, located

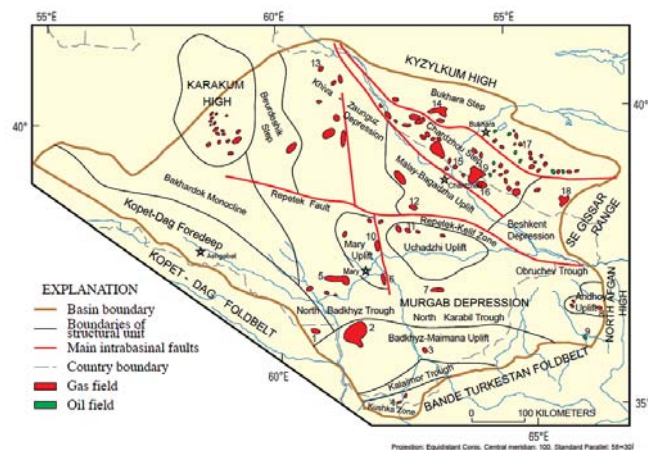


Fig.4. Structure map of Amu-Darya basin showing oil and gas fields

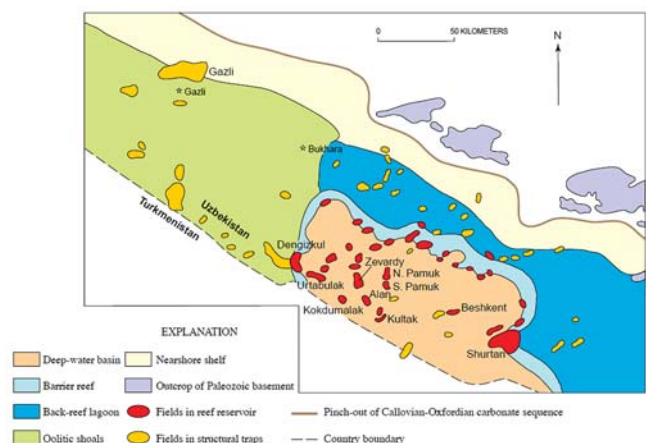


Fig.5. Paleogeographic map of the Bukhara-Khiva region for Oxfordian time

reserves in the near future are connected with Paleogene and Neogene deposits of the Central-Fergana depression. Because these systems are buried deeply (up to 5km and more), the eastern part of a hollow to which the Andizhan group of fields joins on the southern stage and Izbaskent-Maylisuy - on the northern stage can be considered as priority zone. Depth of expected presence of Paleogene deposits should be more than 4km.

Besides, the southern part of the North Fergana step is given the priority for conducting exploration where there are identified oil fields. In addition to the Paleogene and Neogene deposits, certain prospects are associated with the Cretaceous and Paleozoic formations.

The total amount of provable recoverable hydrocarbon resources of the Fergana region is about 500 million tons of oil equivalent.

3. Conclusions

In the Republic of Uzbekistan the total area of the potential lands with established industrial productivity is 203,700km². In addition, the area of two potential oil and gas regions (Khorezm and Mid-Syrdarya) adds up to 78,700km², on which provable recoverable reserves are around 900 million tons of oil equivalent. In other words, more than 63% of the total territory of the republic is potential on oil and gas.

During the whole exploration periods in the Republic of Uzbekistan, 243 oil and gas fields have been discovered. Among them, 112 (46%) fields were discovered over the years of independence (since 1991). In terms of phase conditions, they are classified as follows: 10 gas fields; 116 gas-condensate fields; 66 oil and gas and oil-gas-condensate fields; and 51 oil fields. In terms of development level, they are categorised as follows: 104 are under development, 79 are ready for development and suspension, and 60 are under evaluation process.

One of the criteria for evaluation of exploration performances is oil and gas discoveries. During 2005 - 2012, 58 oil and gas fields were discovered in the Republic of Uzbekistan. Thus, the average number of discoveries annually fluctuates from 2 in 2012 to 13 in 2008. At the same time, 168 new oil and gas potential structures have been put into the deep drilling process. The success rate of field discovery over the years ranges from 0.13 in 2012 to 0.63 in 2011, and 0.35 on average for five years. This corresponds to the world's average level.

The analysis of exploration work's results in the Republic of Uzbekistan testifies that the hydrocarbon potential of oil and gas regions in the country is still very high and it is advisable to carry out further searches for oil and gas accumulation. The availability of provable reserves of hydrocarbon of more than 9.5 billion tons of oil equivalent allows increasing volumes of exploration work, and attracting foreign investors to build up resource base of hydrocarbons. It is also promoted by the specific geopolitical position of Uzbekistan, with its favourable regulatory and legal framework, developed system of gas pipelines, and oil and gas processing complexes.

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PETROVIETNAM NEWS

First oil from Su Tu Nau and Su Tu Vang Southwest fields

Cuu Long Joint Operating Company (Cuu Long JOC) held a grand ceremony to celebrate the first oil from the Su Tu Nau and Su Tu Vang Southwest fields (Block 15-1) on 24 October 2014 in Ho Chi Minh City. At the ceremony, Deputy Prime Minister Hoang Trung Hai awarded the First Class Labour Medal to Cuu Long JOC and many other honourable awards.

First oil from the Su Tu Nau field was achieved at 10:45 AM on 14 September 2014, 47 days earlier than the plan. The Su Tu Vang Southwest field produced its first oil at 10:10 AM on 19 September 2014 and has the shortest development time (over 10 months) among oil and gas fields in Vietnam. This is very important as they contribute to ensuring the national energy security.

According to Dr. Nguyen Van Que, General Director of Cuu Long JOC, the early launch of these two fields' production (with total investment of approx. USD 870 million) will increase the whole project's turnover in 2014 by nearly USD 100 million, and raise the total production of Block 15-1 to nearly 80,000 barrels per day. Oil production of Cuu Long JOC is expected to reach more than 2.24 million tons, thus creating the firm precondition for implementing a production plan with higher goals in 2015 and in the coming years.



Deputy Prime Minister Hoang Trung Hai and delegates welcomes first oil from Su Tu Nau and Su Tu Vang Southwest. Photo: Le Khoa

The close collaboration between the Petrovietnam Exploration and Production Corporation (PVEP - holding 50% stake in Block 15.1), Cuu Long JOC operator, partners in the joint venture, and the consortium of contractors in the process of project implementation has helped to significantly shorten the deployment time, thus bringing the project into production earlier than schedule. The success of the project will open the prospect for development of small and marginal fields in the Cuu Long basin and in other regions of Vietnam in the future.

Le Khoa

Petrovietnam and ENI strengthen co-operation



Minister of Industry and Trade Vu Huy Hoang and Petrovietnam Chairman Nguyen Xuan Son witnessed the signing of co-operation agreement between ENI and PVEP. Photo: PVEP

On 16 October 2014, Minister of Industry and Trade Vu Huy Hoang and Petrovietnam Chairman Nguyen Xuan Son visited and worked with senior leaders of ENI S.p.A in the Republic of Italy.

Minister Vu Huy Hoang appreciated the co-operation between ENI and Petrovietnam in investment and

development of oil and gas projects in Vietnam and hoped the two sides continue to strengthen their co-operation in the future, first of all co-operation in lots MD-2 and MD-4 (two petroleum blocks located offshore Myanmar), which ENI and Petrovietnam Exploration and Production Corporation (PVEP), a subsidiary of Petrovietnam, have recently been awarded.

Minister of Industry and Trade Vu Huy Hoang, Petrovietnam's and ENI's leaders witnessed the signing ceremony of co-operation agreement between PVEP and ENI.

Earlier, on 15 October 2014, the Chairman of Petrovietnam visited Berlin gas turbine manufacturing plant and worked with Siemens' leaders. Siemens has supplied major equipment and maintenance services for Petrovietnam's power plants such as Ca Mau 1 & 2, and Nhon Trach 2. Mr. Nguyen Xuan Son highly appreciated Siemens' capacity in manufacturing turbines and products of modern technology, and stated that Petrovietnam will promote co-operation with Siemens in the coming period.

Manh Hoa

Workshop on Planning for Future Challenges and Opportunities



Senior expert of IHS at the workshop. Photo: Pham Mai

The Vietnam Petroleum Institute (VPI) and IHS (US) held a Collaboration Workshop on "Planning for Future Challenges and Opportunities" on 21 October 2014 in Hanoi. Attending this workshop were IHS leaders responsible for Asia-Pacific, its directors for energy sales and upstream consulting, and the leaders and senior experts of Petrovietnam.

The workshop discussed and evaluated the development trends of the world and regional oil and gas industry; analysed data and technical reports on upstream activities in the Asia-Pacific region; and explored the opportunities

and challenges for deepwater exploration and production of oil and gas, EOR and development of marginal fields, and the prospects of petrochemical sector development in Asia, especially of naphtha production from low-cost supplies from North America and the Middle East, etc.

At the workshop, Dr. Phan Ngoc Trung, Director of the Vietnam Petroleum Institute, gave a brief outline of Petrovietnam's development in recent years with the creation of a complete value chain of oil and gas industry from exploration and production of oil and gas to processing, transportation, storage and distribution of petroleum products. "Petrovietnam is now a leading economic group of Vietnam and has contributed greatly to the socio-economic development, energy security, and national sovereignty of the country."

Dr. Phan Ngoc Trung affirmed that Petrovietnam/VPI highly appreciated the information presented by IHS at the workshop and expressed his hope that the two sides will strengthen co-operation, creating strong development in enhancing the quality of researches and studies, particularly in the field of oil and gas exploration and production.

Xuan Son

Petrovietnam leaders works with BSR

On 22 October 2014, the delegation of the Vietnam Oil and Gas Group (Petrovietnam) worked with Binh Son Refining and Petrochemical Company Limited (BSR) on production and business results of the first 10 months of 2014 and the yearly plan for 2015.

In the first 10 months of 2014, BSR has produced nearly 4.7 million tons of products, which is equal to 97% of the yearly plan; completed the 2nd overall maintenance of Dung Quat Refinery earlier than schedule; earned a total revenue of VND 105.6 trillion, equivalent to 106% of the yearly plan; contributed to the State Budget an estimated amount of VND 19.2 trillion, equal to 159% of the yearly plan. In particular, BSR has been blending and trading gasoline E5 from 30 July 2014. To date, BSR has produced over

9 million litres of gasoline E5, and sold out 8.8 million litres.

Petrovietnam leaders appreciated the production and business results of BSR in recent years. The company's major tasks in 2015 is to continue to operate the plant safely and stably and with improved efficiency; carry out equitisation so that BSR will operate as a limited liability company with 2 members or as a joint stock company; continue to implement the plan to expand and upgrade Dung Quat Refinery and other investment projects according to the schedule.

On the same day, the delegation of Petrovietnam had a meeting with leaders of the People's Committee of Quang Ngai province on the plan to expand and upgrade Dung Quat Refinery.

Minh Sy

KEEL LAYING CEREMONY FOR TAM DAO 05 JACK-UP RIG

Vietsovpetro Joint Venture and Petrovietnam Marine Shipyard Joint Stock Company (PV Shipyard) held a keel laying ceremony for Tam Dao 05 jack-up rig on 25 October 2014 after nearly 12 months of construction. This is the second jack-up rig made by PV Shipyard.

Tam Dao 05 jack-up rig is designed after the JU-2000E model by Friede and Goldman (US) with a total weight of 18,000 tons. The rig has the operation ability at sea water depth of 120m (400ft) and drilling capacity at the depth of 9km (30,000ft). The project is worth more than USD 200 million and expected to be completed after 32 months, 4 months shorter than the fabrication of Tam Dao 03 - the first jack-up rig constructed by PV Shipyard.

The investment in Tam Dao 05 jack-up rig will help Vietsovpetro to be more pro-active in oil and gas exploration and production, and reduce the cost of hiring drilling rigs from foreign contractors.

Kieu Trang

Lao Deputy Prime Minister visits Petrovietnam

During a state visit to Vietnam, Deputy Prime Minister of the Lao People's Democratic Republic Somsavath Lengsavad and his delegation came to visit and work with the Vietnam Oil and Gas Group (Petrovietnam) on 27 September 2014 in Hanoi. The delegation was welcomed by Deputy Minister of Industry and Trade Cao Quoc Hung, representative of the Government Office, Petrovietnam Vice President Nguyen Quoc Khanh, and representatives of Petrovietnam subsidiaries which have on-going projects in Laos such as PVEP, PV Power and PV OIL.

At the meeting, Deputy Prime Minister Somsavath Lengsavad highly appreciated Petrovietnam's development in the past years, deserving the key position in the economy of Vietnam. He also announced the working results between his delegation and the Government of Vietnam to further promote the comprehensive co-operation between the two countries, especially in energy issues, to solve problems and difficulties, and strive to reach a trade turnover of nearly USD 2 billion between the two countries by 2015. Specifically with Petrovietnam, the neighbouring country is actively working with related parties to accelerate the Luang Prabang Hydropower Project, which is executed by PV Power.



Lao Deputy Prime Minister Somsavath Lengsavad at a meeting with Petrovietnam. Photo: PVN

Petrovietnam Vice President Nguyen Quoc Khanh affirmed to follow the two Governments' guidelines to further promote co-operation activities with the Lao People's Democratic Republic, particularly the Luang Prabang Hydropower Project. Mr. Nguyen Quoc Khanh also hoped the Lao Government would consider and approve Petrovietnam's proposals during the implementation of Luang Prabang Hydropower Project to enhance its investment efficiency.

Minh Doan

Petrovietnam leader works with Grace Davison on co-operation in the field of catalysis and petroleum chemicals

On 4 October, Petrovietnam Vice President Le Manh Hung visited and worked with Grace Davison on co-operation in the field of catalysis and petroleum chemicals.

At the meeting, the leaders of Petrovietnam and Grace Davison discussed the handling of technical problems of petroleum catalysts, including the catalysts for Dung Quat Refinery, investment co-operation possibilities for FCC plant in Vietnam; and visited the catalyst production plant and laboratories to evaluate Grace Davison's catalyst.

Grace Davison expressed the interest in long-term co-operation with

Petrovietnam in providing catalysts as well as supporting technical problems for the petrochemical refineries. Both parties agreed to establish a working group for the study and detailed assessment of comprehensive co-operation possibility with Petrovietnam in the field of catalysis and chemicals, including the FCC catalyst production plant in Vietnam.

Grace Davison is among the world's top suppliers of catalysts, chemicals and engineering solutions for petrochemical and refining industry, particularly catalysts for FCC, hydrocracking, and hydrotreating workshops. Grace Davison has participated in supplying FCC catalyst for Dung Quat Refinery.

Nguyen Tu

LOAD-OUT OF JACKET FOR WELLHEAD PLATFORM BK4A

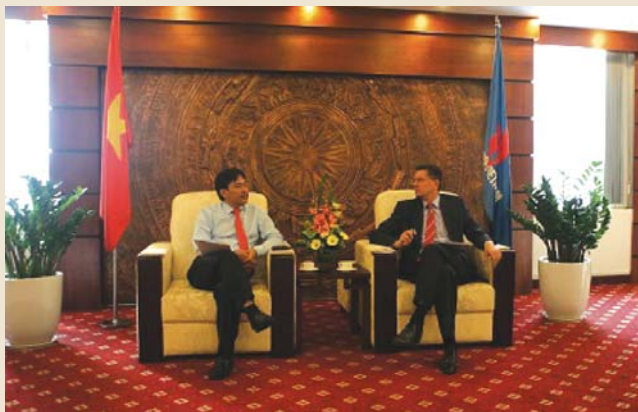


Jacket of WHP BK4A. Photo: VSP

On 10 October 2014, Vietsov-pectro successfully loaded out the jacket of wellhead platform BK4A to prepare for installation at sea. The Wellhead platform BK4A Project includes 1 jacket weighing 600 tons, 1 boat dock access of 90 tons, 12 pile sections of over 640 tons, 1 topside of 420 tons, and 1 bridge linking BK4 and BK4A. This is an important item of the Bach Ho infrastructure upgrading project to receive gas from Thien Ung and Dai Hung fields.

Tran Quang

Petrovietnam leader welcomes Ubifrance



Petrovietnam Vice President Nguyen Hung Dung worked with Ubifrance Chief Representative Marc Cagnard. Photo: PVN

On 14 October 2014, Petrovietnam Vice President Nguyen Hung Dung welcomed and worked with Mr. Marc Cagnard, Commercial Counsellor, Chief Representative of Ubifrance under the French Embassy,

Mr. Michael Chauvin, Director of IS Industrie; Ms. Nguyen Thi Tuyet Lan, Energy Attaché of Ubifrance in Vietnam. The Petrovietnam's leader confirmed that the Group wishes to promote co-operation with French companies in the petroleum and energy sectors.

At the meeting, Mr. Marc Cagnard thanked Petrovietnam for sending representatives to attend the event "Meet Vietnam" (which was jointly held by the Ministry of Industry and Trade of Vietnam and Ubifrance in Paris). Mr. Marc Cagnard introduced IS Industrie (a branch in Thailand of Institut de Soudure - France) and hoped that IS Industrie would become a partner of Petrovietnam in the coming period, providing high-tech solutions in testing and maintenance of industrial equipment, particularly in the power and petroleum sectors: industrial inspection, non-destructive inspection, corrosion treatment, training and granting of certificates.

Manh Chung

PV Drilling and UOD supply service jack-up rig to Hoang Long JOC



Contract signing ceremony between Hoang Long JOC and PV Drilling - UOD. Photo: PVD

Petrovietnam Drilling and Well Services Corporation (PV Drilling) announced it has signed two contracts for the provision of jack-up rig UMW-NAGA 2 and UMW-NAGA 3 to Hoang Long Joint Operating Company (Hoang Long JOC)'s drilling campaigns.

According to the signed contracts, UMW-NAGA 2 rig will continue to be used for campaign appraisal and development drilling in Te Giac Trang field for a period of 12 months. Besides, PV Drilling signed a new contract to provide jack-up rig UMW-NAGA 3 to Hoang Long JOC's new

drilling campaign in Te Giac Trang field, expected to begin in October 2014. These are two jack-up rigs which PV Drilling hired from UOD.

Along with efficient operation of its wholly owned drilling rigs, PV Drilling is co-operating with international oil contractors to provide services to oil companies that are operating in Vietnam. This is the new opportunity for PV Drilling to enhance its professionalism in drilling rig service provision and increase its market share for this type of services in Vietnam.

Ngoc Phuong

THAI BINH 2 THERMAL POWER PLANT: ERECTION OF BOILER 2 STEEL STRUCTURE



On 10 October 2014, the ceremony for erection of boiler 2 steel structure for Thai Binh 2 Thermal Power Plant Project was organised with participation of Petrovietnam, PVC and relevant contractors at Thai Binh 2 Thermal Power Plant Project. This package will be executed by Lilama 69-1 subcontractor. The steel structure of the 1st floor will be installed at the elevation from -0.7 to +13.7m with the total volume of 1,500 tons on the area of 62m².

On the same day, PVC's North Branch started the test pile driving for the power island of Thai Binh 2 Thermal Power Plant Project. It is expected that the package will be completed in September 2015.

Viet Duy

PVPower Coal signs a coal import contract for thermal power plants

On 3 October 2014 in Hanoi, the Petrovietnam Coal Import and Supply Company (PVPower Coal) signed a framework contract on long-term coal purchase with Bukit Asam and Prima Multi Mineral (Indonesia).

According to the signed contract, PV Power will import about 2 million tons per year from Bukit Asam and 1 million tons per year from Prima Multi Mineral, thus ensuring import of coal for at least 10 years. Currently, PV Power is managing 5 thermal power plant projects, with a total capacity of 6,000MW, among which 3 projects, Long Phu 1, Quang Trach 1 and Song Hau, will use the imported coal.

Petrovietnam Vice President Nguyen Hung Dung believed relations between Vietnam and Indonesia in the field of import and export of coal will grow, ensuring a long-term and stable coal supply for thermal power projects in Vietnam. He appreciated the efforts of PV Power in actively seeking additional sources of high-quality coal



Leaders of the PVPower Coal signed a framework contract with Bukit Asam and Multi Mineral. Photo: PV Power

from abroad. The Petrovietnam leader asked PV Power to contact and work with shipping service suppliers, prepare plans for transportation and transshipment of coal for thermal power plants in the coming period.

Nguyen Hang

Contract signed for construction of tight coal storages for Thai Binh 2 Thermal Power Project



Contract signing ceremony between PVC and the consortium of contractors PVC-TB/PVSD/CCU. Photo: PVC

On October 6, 2014, Petrovietnam Construction Joint Stock Corporation (PVC) and the consortium of contractors PVC-TB/PVSD/CCU signed a contract for the "Design, estimate, supply and installation of steel structures and construction of 3 tight storages" package for Thai Binh 2 Thermal Power Plant with a value of over VND 914 billion.

On the same day, PVC and the consortium of contractors Thanh Trang

Investment, Trade and Transportation JSC Company and Tagi Logistics Co., Ltd. signed a supplemental appendix for the contract "Customs clearance and domestic transportation of the main equipment packages" of the Thai Binh 2 Thermal Power Plant. The supplemental works include: loading, unloading and transporting goods within the construction site, building docks and temporary roads for connecting them, reinforcing and building temporary roads within the construction site.

Thai Binh 2 Thermal Power Plant is an important project in the Power Master Plan 7 with Petrovietnam acting as its investor. The plant is designed with two units, a total capacity of 1,200MW and an electricity sale of about 6.7 billion kWh per year. Its total investment is more than USD 1.656 billion with a proportion of owner's fund/loan of 30/70.

Nguyen Thuy

PV GAS AND PVCOMBANK SIGNED A COMPREHENSIVE CO-OPERATION AGREEMENT



Signing ceremony of comprehensive co-operation agreement. Photo: PVFC

Petrovietnam Gas Joint Stock Corporation (PV GAS) and Vietnam Public Commercial Joint Stock Bank (PVcomBank) signed a comprehensive co-operation agreement on 24 October 2014 in Da Lat. Accordingly, priority will be given by PV GAS to using PVcomBank's products and services such as deposits, account billing, credit and capital arrangements, investment co-operation, financial advice, personal financial services and other services.

Ngoc Anh



GLOBAL MARKET

PT Pertamina Malaysia Eksplorasi Produksi has agreed to acquire 30% of the Malaysian oil and gas assets belonging to Murphy Sabah Oil Co., Ltd. and Murphy Sarawak Oil, both wholly owned units of Murphy Oil Corp., for USD 2 billion in cash. The two firms will work jointly in a long-term partnership in which Murphy will remain operator. Murphy says it will continue to execute its development plans and expand through exploration in both deepwater and shallow-water Malaysia. The deal, which needs approval from Malaysia's state owned Petronas, is effective January 1. The first and second phases are expected to close in this year's fourth quarter and first-quarter 2015, respectively.

Shell has completed a deal in which it acquires 155,000 net acres in the *Marcellus* and *Utica* areas of Pennsylvania and receives a cash payment of USD 925 million from Ultra Petroleum Corp., in exchange for Shell's 19,000 net acres of leasehold interest in the Pinedale of Wyoming, including associated gathering and processing contracts. Shell receives 63,000 net acres in the Marshlands area as well as 92,000 net acres in the Tioga area of mutual interest (AMI), an unincorporated joint venture with Ultra, giving Shell 100% interest in Tioga AMI. Ultra's first-half net production from the Marcellus and Utica assets averaged 109 million ft³/day. The assets received by Ultra encompass 1,108 gross wells and associated facilities, and an average of 0.7% overriding royalty interest in 11,500 acres. Shell's second-quarter net production from Pinedale totaled 190 million ft³/day of dry gas.

A subsidiary of EnLink Midstream Partners LP and EnLink Midstream LLC has agreed to acquire Gulf Coast natural gas pipeline assets including the Bridgeline system predominantly located in Southern Louisiana, from Chevron Pipe Line Co. and Chevron Midstream Pipelines LLC for USD 235 million. The natural gas assets include 985 miles of gas pipelines in Southern Louisiana with a total system capacity of 920,000 million ft³/day; 150 miles of gas pipelines in Texas

and Southern Louisiana with a total capacity of 235,000 million ft³/day; 215 miles of offshore Mississippi and Alabama pipelines with a total capacity of 330,000 million ft³/day; storage assets with a combined working capacity of 11 billion ft³ and ownership and management of the title tracking services offered at Henry Hub.

Algeria's Energy Ministry has awarded Statoil ASA and Royal Dutch Shell PLC the 2,730km² Timissit permit license in the Illizi-Ghadames basin in the southeast part of the country. This area holds a potentially large-shale resource play. The first exploration phase is expected to last up to 2017 and include the drilling of two wells and seismic acquisition.

TC Pipelines (TCPL) has agreed to acquire the remaining 30% interest in Bison Pipeline LLC from TransCanada Corp. for USD 215 million. The Bison pipeline transports Rocky Mountain natural gas to the US Midwest through a connection with the partnership's Northern Border Pipeline. The pipeline is supported by long-term ship-or-pay contracts that extend through 2020. TCPL in 2013 acquired an additional 45% interest Bison Pipeline from TransCanada Corp. as part of a USD 1.05 billion deal, expanding TCPL's overall interest at the time to 70% from 25%.

Enagás and Fluxys have signed an agreement to acquire 19% of Total and E.ON's stake in the company that is developing has joined the Trans Adriatic Pipeline AG (TAP) project, in which Enagás will hold a 16% stake. TAP's shareholding is now comprised of BP (20%), SOCAR (20%), Statoil (20%), Fluxys (19%), Enagás (16%) and Axpo (5%). TAP will transport natural gas from the giant Shah Deniz II field in Azerbaijan to Europe. The 871km long pipeline will connect with Trans Anatolian Pipeline near the Turkish-Greek border at Kipoi, cross Greece and Albania and the Adriatic Sea, before coming ashore in southern Italy.

Total plans asset divestment during 2015 - 2017

From 2012 to now Total SA has carried out a plan to restructure its business activity for enforcement of its financial discipline and improvement of its cash flow. The divestment of USD 15 billion in assets included the recent sale of 10% interest in Azerbaijan's Shah Deniz field and the South Caucasus pipeline to Turkish Petroleum Corp. for USD 1.5 billion during 2012-2014. Now Total plans to divest a further USD 10 billion in assets during 2015 - 2017. By this measure Total hopes to reduce its investment to USD 25 billion in 2017. It is targeting USD 15 billion in free cash flow for boosting production to 2.8 million barrels/day that year.

Egyptian General Petroleum Corp. (EGPC) has awarded two concessions in the Gulf of Suez to RWE Dea AG, which will operate and hold 100% in East Ras Fanar Offshore and 50% in Northwest El Amal, with Edison International SPA holding 50%. These two areas cover 552km² in the central and southern gulfs.

Fort Hills Energy LP consortium has let a USD 1.3 billion engineering, procurement, fabrication, and construction contract to Fluor Corp. for the utilities scope of the Fort Hills oil sands mining project, in the Athabasca region. Production is expected to launch in fourth-quarter 2017 and eventually yield 180,000 barrels/day of bitumen.

Lima Refining Co. (LRC), a subsidiary of Husky Energy Inc., has entered an integrated supply contract with a subsidiary of Linde Group as part of a planned upgrade and modernisation project at its 160,000 barrels/day refinery at Lima, Ohio. While Linde expects to invest about USD 100 million overall for related enhancements to its regional hydrogen production operations, a value of the integrated supply contract with LRC was not disclosed. Under the integrated supply agreement, New Jersey-based Linde North America will supply hydrogen and steam utilities to the refinery as LRC implements a crude oil feedstock flexibility project at the site. LRC will use the additional hydrogen to hydrotreat product streams containing sulfur and other components. The new SMR plant, Linde Lima 3, should be on stream during first-quarter 2016.

Petron Corp., has let a contract to a subsidiary of Foster Wheeler's global engineering and construction group for work related to a new delayed coking unit at Petron's 180,000 barrels/day refinery in Limay, about 150km southwest of Manila. The unit, based on Foster Wheeler's proprietary SYDEC delayed coking technology, also includes a Foster Wheeler delayed coker heater.

Foster Wheeler will provide operator training, commissioning, and start-up assistance services for the unit. Foster Wheeler's scope of work is scheduled to be completed by yearend.

Mexican energy reform is the most significant economic and political event in Mexico's recent history. Mexico expects to publish draft technical bidding requirement for its first competitive upstream oil and gas bid round in November 2014. A finalised set of rules will be released in March 2015, and the first bid round is set to follow midyear.

Mexico has passed 9 new laws and amended provisions related to 12 existing laws that provide a framework for private participation in the energy sector that has, for 75 years, been exclusive domain of Pemex.

Round One is expected to offer 109 exploration blocks and 60 producing blocks covering 28,500km². The majority of acreage, 91%, will be for exploration areas and the remaining 9% will be for extraction projects. The areas contain 3,782 million barrels of oil equivalent in proved and probable reserves, and 14,606 million barrels of oil equivalent in prospective resources.

The government has selected four contract types for Round One bidders. These are: licenses, production-sharing agreements, profit-sharing agreements, and service contracts. Only licenses and PSAs would allow winning bidders to own a portion of production at the wellhead.

Mexico appeared poised to become one of the largest oil producers in the world in 2004, when crude production peaked at 3.4 million barrels/day. Output has since fallen to 2.5 million barrels/day as offshore production decreased. Natural gas production has declined to 5.6 billion ft³/day from a peak of 8 billion ft³/day in 2013. Mexico is now a net importer of gas and refined products, bringing in roughly 1.4 billion ft³/day of gas, 80,000 barrels/day of liquefied petroleum gas and 400,000 barrels/day of gasoline. Energy reform is expected to stabilise oil and gas production in the next years.

Crude oil and gas market

By the beginning of October 2014, the Crude Oil Index dropped to USD 95 and predictions of further falls down to USD 90/barrel hold sway for Brent. On the other hand, by 2014, the USA only needs to import 30% of its oil consumption. As unconventional oil production increased, the USA switches from being a net importer to a net exporter of oil.

Back to the Middle East, IS controlled a small oil field in Northern Syria. Because IS does not have access to international markets, it sells its oil in Turkey with a very low price. IS oil sales now account for about 3.5% of Turkey's oil supply, which is not a significant portion of the world market. Although increases in US production were predicted, no one foresaw the great leap in production seen this year. Beside this, the global economic recessions reduce the demand for fuel and raw materials. Consequently, the future oil price cannot recover in the short time.

US tight oil prices after 2020 could fall compared with international benchmarks, resulting in improved oil wellhead margins by 5 USD/barrel. This forecast is based on the additional volumes from enhanced oil recovery (EOR) slated to come on stream after 2020 which could boost tight oil production in the US by 1.5 - 3 million barrels/day by 2030, up to 25% more oil than is being forecasted today, according to analysis from Wood Mackenzie. Although the EOR development technology and techniques are in early test phases and not yet commercial, but indicators suggest up to a 100% increase in recovery rates. Excessive production could drive down US prices by more than 30USD/barrel compared with their international benchmarks. Policymakers could lift the export ban to preserve current investment levels if US crude prices fall compared with international benchmarks, resulting in improved US tight oil wellhead margins. The margin improvement would then attract additional investment, which could yield additional production of 400,000 barrels/day over 5 years. This forecast opens a great enthusiasm for US petroleum industry which will have a positive influence on the future world oil prices.

NGSA forecasts lower winter US gas prices

In its 14th annual Winter Outlook assessment of the natural gas market, the Natural Gas Supply Association (NGSA) expects downward price pressure on the natural gas market compared with last winter. This assessment is based on a combined analysis of the economy, weather, demand production, and storage.

Anticipated return to normal winter weather compared to last year's extreme cold will drive down overall gas demand to 87.7 billion ft³/day, which is 3.4 billion ft³/day less than last winter's record demand levels. Demand from the weather-sensitive residential and commercial sectors, representing more than 40% of customer demand in the winter, will decline and mask growth in other sectors this winter. Gas use from the electric sector is expected to increase very slightly compared to last winter, primarily due

to more "fuel switching" when utilities temporarily switch to using gas-fired power plants due to lower fuel costs.

US production has increased due to drilling activity and system events increasing flowing gas supplies. US production this winter will reach 70.8 billion ft³/day compared with 67.2 billion ft³/day last year. Net imports for the forthcoming winter are expected to be about 3.2 billion ft³/day, 20% less than the net import for the last winter.

Storage inventories at the beginning of the winter season will be adequate. More specifically, average storage withdrawals this winter are projected to be only 12.9 billion ft³/day, or 35% below last winter's record storage withdrawal of 19.7 billion ft³/day.

Average growth in gross domestic product similar to last winter is expected, which exerts a neutral effect on gas prices.

Because of the expected reduction in winter gas consumption and reduced requirements for storage withdrawals, total gas supply for the forthcoming winter will be 4bcfd, which is less than that for last winter.

According to Bloomberg.com (October 13, 2014), Spain's Gas Natural SDG (GAS) offered as much as 2.6 billion euros (USD 3.3 billion) for Chile's Cia. General de Electricidad SA (CGE), which will be its biggest acquisition in 6 years, as the Spanish gas supplier seeks to expand into new markets.

Gas Natural agreed to acquire 54% of CGE from a group of controlling stakeholders and will make a tender offer for the remaining shares, the Barcelona-based utility said yesterday in a statement. Gas Natural will offer 4,700 Chilean pesos (USD 7.94) a share. By acquiring CGE, Gas Natural will be Chile's largest electricity distributor, with 40% market share, as well as the country's biggest power transmission line operator. It will also control natural gas distributor Metrogas SA. For Natural Gas, this operation is a key strategic landmark because it allows it to enter the Chilean energy market from a leadership position.

Petrochemical product markets

Oil and gas analysts forecast that global propylene production capacity will increase to 165 million tons/year by 2030 from a current 109 million tons/year. "The USD 120 billion global market has regularly been in a shortage situation over the past 4 years, causing high prices, and therefore, a loss of market share relative to competing materials", says Stephen Zinger, head of Wood Mackenzie's chemical research for the Americas.

As a result of these supply shortages from steam crackers and refineries, substantial investments have poured into alternative technologies to boost global propylene supplies, including methanol-to-olefins (MTO), methanol-to-propylene (MTP) and propane dehydrogenation (PDH). In addition to creating near-term threats of oversupply in China and North America, these investments in MTO, MTP, and PDH technologies over the next 5 years also will permanently alter the paradigm of propylene's global supply, and market pricing dynamics.

The wide adoption of PDH technology likely is to occur in North America, where ample supplies of domestic shale gas are adding downward pressure to the cost of propane used as feedstock for PDH units. In addition to other new PDH units and expansions under consideration by C3 Petrochemicals (Ascend), Formosa Plastics, Petrologistics, RExtac, and Williams Energy Canada, Dow Chemical Co.

and Enterprise Products Partners LP each are spending more than USD 1 billion to construct and start up new PDH units by early 2016.

Following start-up of these two new PDH units, North American propylene prices likely start to decline as the market becomes saturated with supplies. Although propane prices have been low and PDH profit margins have been very strong for the past 4 years, this trend is expected to dramatically change after the start-up of these new PDH units and several new propane export terminals, causing propane prices to rise and the spread between propylene and propane to return closer to historical levels.

In an attempt to avoid this impending risk of higher propane feedstocks prices for PDH units, BASF is investing MTP technology using natural gas as feedstock for the methanol intermediate chemical. Between 2005 and 2030, the market share of PDH and MTO-MTP-sourced propylene will increase from nonexistent to more than 25% of total North American supply, adding that this will represent a permanent change in the paradigm of marginal propylene supplies to the market.

Between 2005 and 2030, oil analysts forecast the market share of propylene sourced from PDH and MTO-MTP technologies will increase to about 45% of China's total capacity, pushing the country toward full self-sufficiency and negatively impacting export-oriented producers in South Korea, Saudi Arabia, Taiwan, Singapore, and India, which currently serve as China's largest sources of propylene-derivative imports.

Another driver behind the wave of investment in China's on-purpose propylene capacity is a strategy on the part of independent propylene-derivative manufacturers to reduce their dependence on imports and domestic supply from the oligopoly of state-owned majors.

While North America and China are addressing their propylene shortfalls with alternative technologies and feedstocks, Europe would solve imbalances to its propylene supply with additional imports. European crackers are shifting to lighter feeds where possible as evident by the announced intentions to import ethane from the US by Ineos, SABIC, and Borealis, while others continue to study similar options. Currently, there are two PDH units in Europe, but all indications are that new PDH and MTO-MTP investments are not viable options.

Collected by **Ha Phong**

Table 1. Worldwide NGL production (1,000 barrels/day)

	June 2014	May 2014	6 month average production (2014)
Brazil	87	89	84
Canada	650	640	673
Mexico	360	366	364
United States	3,044	2,880	2,827
Venezuela	213	213	213
Other Western Hemisphere	220	233	238
Western Hemisphere	4,574	4,421	4,399
Norway	292	290	308
United Kingdom	51	64	64
Other Western Europe	10	10	10
Western Europe	353	364	382
Russia	457	457	458
Other FSU	165	165	167
Other Eastern Europe	13	13	14
Eastern Europe	635	635	639
Algeria	340	340	340
Egypt	174	174	174
Libya	40	40	43
Other Africa	83	83	82
Africa	637	637	639
Saudi Arabia	1,830	1,830	1,830
UAE	400	400	400
Other Middle East	691	691	668
Middle East	2,921	2,921	2,898
Australia	80	80	74
China	-	-	-
India	100	100	102
Other Asia - Pacific	330	327	337
Asia - Pacific	510	507	513
Total World	9,630	9,484	9,470

Source: Oil & Gas Journal, October 6, 2014

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