Scientific Report

on the

ESF exploratory workshop

"Natural Hydrocarbon Seeps, Global Tectonics and Greenhouse gas Emission"

27-28 August 2001

Delft University of Technology
Department of Applied Earth Sciences
Mijnbouwstraat 120
Delft

Prof. Dr. F.D. van der Meer *Workshop Chairman*
Dr. K.H. Scholte *Workshop Co-Chairman*

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Scientific content of the workshop

The occurrence at the surface above oil and gas reservoirs of hydrocarbon seeps suggests that reservoirs leak. Hydrocarbon macroseepages refers to the visible presence of oil seeping to the surface, whereas hydrocarbon microseepages are invisible trace quantities of light hydrocarbons seeping to the surface. Seepage is perceived as a near vertical process resulting in hydrocarbons migrating along chimneys. However, more research is needed to be able to accurately model the buoyant flow of light hydrocarbons to the surface and hence predict their expression at the surface.

Seeps (macro and micro) are important in prospecting for oil and gas. However seeps are also sources of gases, such as methane and carbon dioxide, that contribute to the greenhouse effect. Data of their emissions are potential inputs into global change models. The emission fluxes and quantities of emitted gases due to seeps is, however, at present unknown and no method exists to monitor emissions from these vents. Much research has been done on the detection and monitoring of offshore microseepages, whilst relatively little work has been done on the detection of onshore microseepages and monitoring of the related emissions.

Hydrocarbon microseepage studies are relevant not only to the oil industry as a tool for exploration for oil, but also from an environmental perspective: methane, one of the seeping gases, is a major contributor to the greenhouse effect. It is unclear at present what the global contribution of microseepage is to the natural methane production annually. However local estimates show that this must be significant, for example venting in the North Sea basin has been estimated to release2.6×10^{12} g methane per year into the water column.

Worldwide, there is a correlation between seeps and earthquake activity, where seeps occur predominantly in areas that are tectonically active. The amount of seepage (ppm methane/ethane) potentially is related to the pressure in reservoirs which is related to hydrostatic pressure and changes in lithospheric stress. Thus in natural seepages, a relation between the amount of seeping gas and stress could be envisaged.

Critical issues for studies of fluid seeps at continental margins and for research on offshore seep detection and monitoring which we identified in preparation of the workshop were:

- the relation between seeps and plate tectonics
- fault pressures in relation to emission fluxes of ethane and methane
- the rate of seepage and the flux of hydrocarbons from seeps
- seeps are small, episodic and ephemeral.
- Connecting the subsurface fluid flow to surface seepage

Likely methods to study seeps are satellite remote sensing, sonar backscatter, geochemical sniffer surveys, detecting anomalies in temperature and water chemistry and the study of anomalous biological communities. The workshop aims at bringing together scientists working on the detection and monitoring of hydrocarbon emissions related to oil and gas reservoirs. Various groups of scientists are working independent of each other and with very limited access to each other's data and understanding of their methods. Some groups focus on offshore, other on onshore seeps. Some use field surveying techniques, subsurface exploration methods, sonar and other remote sensing data other geochemical approaches. At present no forum exists where these research groups can interact and exchange and integrate data and results of their studies.

The workshop aimed at:

- Establishing a platform for a world-wide global correlation programme on hydrocarbon seep management and monitoring.
- Defining a common area for testing and integrating various methods for seep detection and monitoring.

The workshops objectives are to better understand the processes involved in seepage and the relation between hydrocarbon seeps and the local and regional geology and tectonic setting in three dimensions. Ultimately the workshop should provide means of extrapolating aerial extent of seep affected areas and emissions to global estimates. The workshop should answer very basic questions on seep distribution world-wide in relation to local, regional and global tectonics. Also we envisage that increased collaboration in this field leads to estimates of global ethane and methane production from leaking oil and gas reservoirs. At present no quantified numbers exists on methane production from hydrocarbon seeps. However it is known that various such sources exist that contribute a sizeable amount of emission to the global carbon cycle adding to global warming. Hence the integration of available data on seep related gas emissions contributes to better global change models. New innovative research proposals will be generated that integrate surface and subsurface measurements of seep and gas emissions and correlate onshore and offshore data with regional and global tectonic and reservoir models.

Hence the structure of the workshops program reflected the issues at stake. The following thematic sessions were organised:

- Greenhouse gas emission rates
- Seismic modeling of seeps
- Tectonic controlling factors of seeps (two sessions)
- The Oil Mud volcanoes of Azerbaijan
- Surface monitoring of seeps
- Gas hydrates and carbonate mounds
- Forum discussion

Workshop organisation

The workshop organisation consisted of:

Chairman	Prof. Dr. Freek van der Meer
Co-Chairman	Drs. Klaas Scholte
ESF Liaison	Philippa Rowe
ESF Delegate	Dr. Svenje Mehlert
Management assistants	Hannie Zwiers, Miranda Duve
Financial Affairs Officer	Boudewijn de Haas
Scientific Affairs Officer	Ijsbrand Haagsma
Webpages	M&M Productions

The plenary lectures were held in Lecture Hall E of the building of the Department of Applied Earth Sciences (Faculty of Civil Engineering and Geosciences) of Delft University of Technology at the Mijnbouwstraat 120 in Delft. The posters were on display from Monday, 27 August, 10:30 until Tuesday, 28 August 2001, 18:00 in the poster area located in the "Grote Vergaderzaal'. Delegates were housed in two nearby hotels:
Juliana Hotel
M. Trompstraat 33
Delft
Tel: 31-15-2567612 / Fax: 31-15-2565707
http://www.hoteljuliana.nl/indexeng.html

Dish Hotel
Kanaalweg 3
Delft
Tel: 31-15-2569358 / Fax: 31-15-2623546
http://www.dishhoteldelft.nl/

In the first hotel, on Sunday evening an ice breaker reception was hosted.

On the evening of the 27th of August a social event was hosted. The first part of the event consisted of a canal boat tour through the canals of Delft. The second part of the social event was the workshop diner at the Grand Café "Johannes Vermeer".

The European Science Foundation was the main sponsor of the event. Beside the ESF, we also were pleased to receive support from the following organizations:

- Center for Technical Geosciences
- Delft University of Technology
- European Science Foundation
- European Association of Remote Sensing Laboratories
- International Institute for Aerospace Survey and Earth Sciences
- Netherlands Organization for Scientific Research
- Shell International Exploration and Production B.V.
- Space Research Organization Netherlands

The workshop included over 20 invited participants that were fully sponsored by the ESF grant. Through direct emailing and the distribution of flyers, we were able to attract over 60 participants to the workshop. All participants participated at no cost and their participation included all social events, lunches and diner. The program was send to speakers and registered participants in the first week of July and (in final form) in the second week of August. Regular updates of the program were posted on the workshops web pages at http://www.hyperspectral.tudelft.nl

Final Programme

The workshop was composed of plenary oral presentations in seven sessions each consisting of 20 min. presentations (15 min. presentation + 5 min. discussion at the discretion of the author). Furthermore the programme included an interactive poster session. On the first day, the authors of the posters have been given the opportunity to orally introduce their work in 2 minutes using 1-2 overhead sheets. The last session of the workshop was devoted to a plenary discussion on future direction of the field.

Sunday, 26 August 2001

Icebreaker party at the Juliana Hotel (for address see section on The Workshop Venue) from 17:00 – 19:00

Monday, 27 August 2001

8:30-9:30 Registration
Room E at the Department of Applied Earth Sciences, Mijnbouwstraat 120, Delft

9:30 – 10:30 Opening session – (Chair: Freek van der Meer)
Prof. F. van der Meer - workshop chair
Prof. K. Wakker – Rector TUD
Prof. C. van Kruijsdijk – Chairman Technical Earth Sciences
Dr. Svenje Mehlert – ESF
Dr. R. de Groot – SRON
Dr. J. Dijkhof – NWO

10:30 – 11:00 Coffee break + Group photo will be taken

11:00 – 12:30 Session I – Greenhouse gas emission rates (Chair: Freek van der Meer)

Smedman, Ann-Sofi (Institutionen för geovetenskaper, meteorologi, Uppsala, Sweden)
How can leakage of gases from seeps increase the green- house effect in the atmosphere?

Woodside, John (Free University Amsterdam, the Netherlands)
Seafloor Methane Emissions in the Eastern Mediterranean Sea

Cramer, Bernhard (BGR, Hannover, Germany)
Emission rates and the geochemistry of seeping gas from different on-shore and off-shore areas

Michiel Roemer[1,*], Peter Zandveld[1], Michiel van Weele[2], Peter van Velthoven[2], Guus Velders[3]
[1]TNO-MEP, PO Box 342, 7300 AH, Apeldoorn,
[2]KNMI, PO Box 201, 3730 AE, De Bilt
[3]RIVM, PO Box 1, 3720 BA, Bilthoven
Methane emission verification by observations on a global and local scale

12:30 – 12:45 Introduction to the posters

P01: Thomas O. Richter (1), Alina Stadnitskaia (1,2), Conxita Taberner (3), Tjeerd C.E. van Weering
Presented by: C. Taberner
Institut de Ciències de la Terra. C/ Lluis Solé i Sabarís s/n, 08028 Barcelona, Spain
Authigenic carbonates in A carbonate mound at Porcupine margin, NE ATLANTIC OCEAN

P02: A. Obdam and P. Cleveringa
National Institute of Applied Geoscience TNO, Groundwater Division, Delft
Shallow gas migration in unconsolidated sediments

P03: Bahman Tohidi, Ross Anderson, Jinhai Yang, Ben Clennell
Department of Petroleum Engineering , Heriot-Watt University, Edinburgh, EH14 4AS, UK
Visual Observation of Gas Hydrate Formation, Growth and Dissociation Using Glass Micromodels

P04: Michal Shimoni[1], Freek van der Meer[1], Ramon Hanssen[2], Bert Kampes[2], and Ben-Dor Eyal[3]
[1]ITC, Geological survey division, The Netherlands.
[2]Delft University of Technology, Faculty of Geodetic Engineering, The Netherlands.
[3]Tel-Aviv University, Department of Geography and Human Environment, Israel.
Detection of Neotectonic Features Combining Advanced Remote Sensing Data, the Case study of the Dead Sea Rift, Southern Israel

P05: Stefan Sommer and Olaf Pfannkuche
GEOMAR Research Center for Marine Geosciences, Wischhofstrasse 1-3, 24148, Kiel, Germany
The Small Sized Benthic Biota in Surficial Marine Gashydrate Sediments

P06: Erik Gutzmann, Stefan Sommer & Olaf Pfannkuche
GEOMAR Research Center for Marine Geosciences, Wischhofstrasse 1-3, 24148, Kiel, Germany
Meiofaunal assemblages in sediments with shallow gas hydrates at the Hydrate Ridge, Cascadia Subduction zone

P07: Harald van der Werff, Freek van der Meer, Paul van Dijk
ITC, Geology Division, Enschede, Netherlands
Hyperspectral detection of hydrocarbon seepage in the Santa Barbara area, Ca.

12:45 - 14:00 Lunch

14:00 – 15:30 Session II: Seismic modeling of seeps (Chair: Sierd Cloetingh)

De Groot, Paul (DgB, Earth Sciences, Enschede, the Netherlands)
Seismic expression of hydrocarbon accumulations and seeps

Heggland, Roar (Statoil, Norway)
The chimney cube for 3D seismic modeling of seeps: recent developments

Henriet, Jean-Pierre & Van Rensbergen, Pieter (University of Gent, Belgium)
The power of high resolution geophysics in resolving fluid migration pathways in deep water carbonate and hydrate provinces.

Bronken-Jacobsen, Janet (NTNU, Institute for Petroleum Geology, Norway)
Hydrocarbon leakage in the Gullfaks overburden, Norwegian North Sea

15:30 – 16:00 Tea break

16:00 – 17:00 Session III: Tectonic controlling factors of seeps – Part 1 (Chair: Michael Abrams)

Cloetingh, Sierd (VU Amsterdam, Netherlands)
Global tectonics and hydrocarbon seeps (prelim)

Somoza, Luis (ITGE, Madrid, Spain)
Hydrocarbon seeps, gas hydrates and carbonate chimneys in the Gulf of Cadiz: An example of the interaction between tectonic and oceanographic controlling factors

Ben-Avraham, Z.[1], Woodside, J.[2], Nur, A.[3], Zurieli, A.[1], Cloetingh, S.[2]
[1] Department of Geophysics and Planetary Sciences, Tel Aviv University
[2] Faculty of Earth Sciences, Free University of Amsterdam
[3] Department of Geophysics, Stanford University
Was there a massive release of methane from destabilised gas hydrates in the Mediterranean during the Messinian salinity crisis?

18:00 start evening programme

Tuesday, 28 August 2001

9:00 – 10:00 Session IV: Tectonic controlling factors of seeps – Part 2 (Chair: Martin Hale)

Michael A. Abrams and Marylin P. Segall (Energy & Geoscience Institute, University of Utah, Salt Lake City, Utah)
Near-Surface Expression of Hydrocarbon Migration: Understanding the Petroleum Seepage System

B.M. Schroot (Netherlands Institute of Applied Geoscience TNO, Department of Geo-Energy, Utrecht)
Observation and detection of seepage and migration of shallow gas in the Southern North Sea

Henri Bougault[1], P. Cochonat[1], A. Gay[1], H. Nouzé, H, Ondreas[1], N. Sultan[1], E. Cauquil[2].
[1]IFREMER, Plouzané, France
[2]TOTALFINAELF, Pau France
Different types of fluid circulation over a passive margin, from the continental shelf to the abyssal plain. Examples from the Gulf of Guinea, ZAIANGO program

10:00 – 10:30 Coffee break

10:30 - 12:00 Session V: The Oil Mud volcanoes of Azerbaijan (Chair: Salle Kroonenberg)

Cooper, Calvin (AGIP, Italy)
Mud volcanoes of Azerbaijan

Simmons, Mike (Cambridge University, CASP group, Cambridge, UK)
An Overview of Petroleum Systems in the South Caspian Basin.

Ibragim S. Guliev, Dadash A. Huseynov and Elmira G. Aliyeva
Institute of Geology of the National Academy of Sciences,
Baku, Republic of Azerbaijan
Mud volcanoes in the South Caspian basin: deep sources and dynamics of development

K.H. Scholte[1], F. van der Meer[1], S. Kroonenberg[1], I.S. Guliev[2], E. Aliyeva[2], D. Huseynov[2], and M. Malkhazov[3]
[1] Delft University of Technology, Applied Earth Sciences, POB 5028, 2600 GA Delft.
[2] Geology Institute, Azerbaijan Academy of Sciences.
[3] Department of Geography, Moscow state University.
Remote sensing data inversion to map onshore oil mud volcanoes in Azerbaijan

12:00 – 13:30 Lunch

13:30 – 15:15 Session VI: Surface monitoring of seeps (Chair: Freek van der Meer)

Hale, Martin (ITC, Netherlands)
Surface geochemistry of oil and gas seeps

Yang Hong, Mark Little, Olaf Podlaha
Shell International E & P, B.V.
Remote sensing in the oil industry

Hanssen, Ramon (TUD)
Millimeter-level subsidence monitoring using recursive spaceborne radar interferometry

Cleverly, Robin (Nigel Press Associates, UK)
From Zoroaster to ASTER: petroleum seepage and exploration

Jeff Hurley (Project Manager, RADARSAT International, Vancouver, British Columbia CANADA)
Offshore Oil Seep Detection using Satellite SAR sensors

15:15 – 15:45 Tea break

15:45 – 17:15 Session VII: Gas hydrates and carbonate mounds (Chair: John Woodside)

Hovland, Martin (Statoil, Stavanger, Norway)
Methane sequestering in near-surface sediments by bacteria, carbonate preciptation and hydration.

Mustafa ErgÜn (Dokuz Eylul University, Izmir Turkey)
Gas saturated sediment accumulations in the Black Sea

Van Weering, Tjeerd (NIOZ, Texel, Netherlands)
Carbonate Mounds and Cold water Corals at the NE Atlantic Ocean Margin.

Marcus Elvert[1], Antje Boetius[1], Dirk Rickert[2], Tina Treude[1], Katja Nauhaus[1] and Katrin Ravenschlag[1]
[1]Max Planck Institute for Marine Microbiology, Celsiusstr. 1,D-28359 Bremen, Germany
[2]GEOMAR Research Center for Marine Geosciences, Wischhofstr. 1-3, D-24148 Kiel, Germany
Anaerobic oxidation of methane mediated by a microbial consortium above marine gas hydrate, Cascadia margin

17:15 – 18:00 Final considerations and discussions

18:00 – Farewell drink

Assessment of the results

Opening session

In the opening session, the Rector Magnificus of Delft University of Technology, Prof. K. Wakker and the director of the department of Applied Earth Sciences of that university highlighted the importance of the workshop to the international science community. Prof. Wakker stated that "Methane is after CO2 one of the prominent gases that play a role in the global change. Many man-induced sources of methane are known, however several natural sources of methane production do also exist. Among these is the emission of methane from natural hydrocarbon seeps. Oil and gas reservoirs leak. As a result, petroleum leaks to the earth surface to form oil and gas seeps. The emission fluxes and quantities of emitted gases due to seeps is at present unknown and no method exists to monitor emissions from these vents. Much work has been done on the detection and monitoring of offshore seepages, whilst relatively little work has been done on the detection of onshore seepages and monitoring of the related emissions." Dr. Dijkhof and Dr. Mehlert on behalf of NWO and ESF discussed the possible instruments for increased European collaboration on the topics of the workshop.

Conclusions:

- Two possible means were identified namely a ESF Network programme and a contribution to the ESF Eurocore on EUROMARGINS.

Greenhouse gas emission rates

The first scientific session dealt with the processes underlying the emissions along seeps and aimed at both the search for methods of quantifying the emission of CO2 and methane locally as well as globally as well as defining the magnitude of emissions. Transport processes in the atmosphere close to the surface were described with the current Monin-Obukhov theory and also deviations from that theory. The green-house effect was discussed and the possible role of seeps therein. We are far away from a global estimate of methane emission from seeps and are just starting to understand how to upscale local estimates to regional and global levels. Only minor amounts of the gaseous hydrocarbons generated in sedimentary basins are accumulated in gas reservoirs. Most of the gas is either dissolved in deep groundwater, sorbed on sedimentary organic matter, bound in gas hydrate lattice, or escapes from the sediments via buoyancy driven or diffusional migration. Tectonic events may initiate the release of formerly bound gas leading to its emanation into the atmosphere. A recent example of a natural emission of thermogenic gas through deep reaching faults is presented from the Münsterland area, Germany, where up to 8 $g/(m^2 \cdot d)$ of methane emanate into the atmosphere. Numerical basin modelling studies quantify petroleum generation and migration and can aid to identify periods of enhanced gas emission in the geological past. Offshore, levels of methane in the water above the mud volcanoes and seeps were found to vary up to about 13.5 µl/l. However due to biogenic oxidation processes most methane does not reach the atmosphere. Much of the gas is also bound in gas hydrate lattices. Losses to the atmosphere due to continuous gas diffusion through the cap rock of a reservoir are considered to be neglectable. For the giant gas fields of West Siberia it is shown that diffusion through the cap rock is 3 to 4 orders of magnitude less effective than the biodegradation processes in the near surface soil. Here methanotrophic microbes consume methane with rates of about 3 $mg/(m^2 \cdot d)$ preventing any continuous emission of deep sourced hydrocarbons into the atmosphere. Gas seeps at the sea floor are widespread. However, emission of methane to the atmosphere is not an issue in offshore areas because part of the ascending methane is already consumed in the sediments below the sea floor. Methane reaching the water column is immediately exposed to microbial consumption. This process together with dilution in ocean

water prevents methane emission into the atmosphere from sediments below deep water. Monitoring of seeps and emissions with remote sensing instruments is starting to become feasible. At a global scale, the SCIAMACHY system on ENVISAT can be used. Local scale instruments are as yet not foreseen.

Conclusions:

- Modeling the emission of greenhouse gases along seeps in the atmosphere and the upscaling of emissions at local vent to regional and global scales is non-trivial. An estimate of the global production of methane along seeps at present cannot be given.
- Emission of greenhouse gases along seeps in offshore areas is limited because of the buffering and oxidation of methane in the shallow subsurface and in deep (>2000m.) water.
- Emission of greenhouse gases along seeps in onshore areas is profound and tectonically controlled. Emission occurs where seeps are fault-controlled and degassing of sedimentary basins occurs during periods of basin inversion. Losses to the atmosphere due to continuous gas diffusion through the cap rock of a reservoir are considered to be neglectable

Seismic modeling of seeps

That hydrocarbon seeps also have an impact on the seismic response has been known for many years as well. Direct evidence of seepage is a so-called chimney, a vertical disturbance of the seismic response. These are caused by saturated fluids and/or free gas migrating through porous rocks. As the fluids move up the pressure drops and solution gas is released. Some gas stays in the pores, thus changing the acoustic properties of the rock. This connate gas affects especially the P-wave velocity. Alternatively, over-pressured fluids may have cracked the rocks causing scattering of the seismic waves. Until recently these disturbances were considered unwanted noise that obscured the reflection energy. The use of modern 3D seismics allows, through statistical classification techniques, to obtain detailed information on the architecture of chimneys and hence on the migration pathways of seeps. On the contrary high resolution seismics allows to detect oil and gas migration effectively in the near surface zone. The presentations in this session showed how advance the seismic processing is too date. Integration of the vertical profile data with surface data is lacking.

Conclusions:

- Advanced image processing in combination with high quality 3D seismic data gives insight into the trajectories of subsurface oil and gas migration in chimneys.
- High resolution seismics fills the gab between surface measurements and subsurface 3D Seismic data.
- Integrating sub-surface seismic data with surface measurement techniques such remote sensing and geochmistry are needed.
- Seismic processing is aimed mainly at detecting and visualising chimneys rather than modeling the processes related to migration of oil and gas along these chimneys.

Tectonic controlling factors of seeps

In the Gulf of Biscay, episodic hydrocarbon seeps caused by salt tectonics and massive hydrate dissociation are probably modulated by sea-level changes and tectonic in response to the advance of crustal thrusting wedges, increase of contourite/shelf wedge sedimentary loading. The relationship between near-surface hydrocarbon seepage and subsurface petroleum generation and entrapment is often very complex. The subsurface to surface migration pathway is determined by the interrelationships of sediment fill, sedimentation rates, tectonics, and fluid flow. A full spectrum of leakage exists for the petroleum seepage system: seepage activity (qualitative expression of comparative leakage rates, active versus passive), seepage type (concentration,

macro versus micro seepage), migration focus (near vertical to lateral displacement), and surface seep distribution (focused from point source, lateral displacement, to dispersed). The rate and volume of hydrocarbon seepage to the surface greatly controls the near-surface geological and biological responses and thus the type of sampling required for the effective detection of hydrocarbon leakage.

Conclusions:

- Tectonics plays a major role in the rate of emissions along seeps both at geologic times where basin degassing is related to tectonics phases of uplift, erosion and inversion as well as in historic changes in the stress field.
- The mechanism of petroleum seepage and hydrocarbon migration from the subsurface reservoirs to the near surface is poorly understood and pathways of oil and gas are complex and intimately linked to the geological architecture of the crust. A better understanding of these migration pathways requires a 3D or 4D visualisation and modelling of the subsurface.

The Oil Mud volcanoes of Azerbaijan

Of the 600 known oil mud volcanoes in the world some 220 are located in the South Caspian Basin (SCB) of Azerbaijan. The mud volcanoes of Azerbaijan are among the world's most impressive examples, for their size, frequency and quantity of ejecta. This session should give answers to the question whether emission of methane along seeps is a local problem with a global effect on the greenhouse effect. On land, mud volcanoes range from massive, explosive cones with well developed calderas and rift valleys, to simple oozing mud pots. The mud ejecta can contain Cretaceous to Recent rock fragments usually in a matrix of Eocene to Miocene shale and mud. The volcanoes are all strictly Quaternary- Recent age features, which corresponds with the timing of formation of over-pressured methane at depth. Mud volcanoes exist only where we have a specific combination of geological factors which include, thermally cold basins with very rapid sedimentation rates, tremendously over-pressured argillaceous shales containing organic matter capable of generating gas, tectonic compression with local extension allowing rupture the gas seal. In the South Caspian basin the thermogenic gas which powers mud volcanoes originates from an organic source rock buried at depths reaching 12-14 km over wide areas. Oil tends to be expelled first and it can be observed that only minor quantities of oil are extruded from the mud volcano eruptions. Instead oil is widely extruded from vents on the shoulders of volcanic edifices related to the seal rupture of shallow oil pools. The South Caspian Basin contains known hydrocarbon reserves in the region of 25 Billion Barrels oil equivalent. Speculative estimates indicate that there is as much again yet to be found. 99% of these reserves are contained within what can be considered as one gross petroleum system. Reservoirs are in the fluvial – deltaic sediments of major river systems entering an isolated South Caspian Basin in the latest Miocene - Early Pliocene; hydrocarbons are sourced from the marine Early Oligocene basal Maykop Suite, with a secondary contribution from the more restricted marine Miocene Diatom Suite; thrust-related anticlinal traps formed from the Late Pliocene onwards with charge occurring simultaneously. Seals are both intraformational, with the Late Pliocene Akchagyl sediments forming a region seal. A working petroleum system is demonstrated by the abundant seepage in and around the margins of the basin, especially the spectacular and relatively common mud volcanoes that the region is well known for. Mud volcanoes can be 500m. high, 4-5 km. in diameter and typical breccia flow products are 20-30m. thick and 3 km. in length. During a eruption of a mud volcanoe in 1958 a gas flame of 120m. wide and 1 km. high flared for several weeks.

Conclusions:

- Estimates of methane emission vary from 530 million m3/km2 methane per year for the SCB (Cooper) to 250 mill m3 gas/year (Guliev); both numbers indicate high significance in terms of global methane production.
- Eruptions of mud volcanoes are violent and represent a geohazard.
- Mud volcano activity is linked with the changes in tectonics regime and seismicity.

Surface monitoring of seeps

Likely methods of monitoring seeps are surface geochemistry and remote sensing. Geochemical has been a proven method for seepage detection onshore at various locations where the typical anomaly has the shape of a Rabbit ear occurring along chimneys. Hyperspectral remote sensing can potentially be used to monitor seeps and in time possibly provide estimates of emission rates. Data from airborne sensors is widely used and new data from the spaceborne ASTER satellite system is now being explored. To monitor surface deformation at millimeter resolution, radar data can be used in combination with a technique based on interferometry. Offshore monitoring of seeps using SAR data is now very advanced and widely used in the environmental as well as in the oil industries.

Conclusions:

- Remote sensing in combination with surface geochemistry could be used to develop a (Onshore) monitoring method for seeps.
- Integration of surface measurements with subsurface imaging data is not been demonstrated but would give assets to both methods.

Gas hydrates and carbonate mounds

Methane from continental shelf regions is of great interest for several reasons. Firstly, measured methane saturation values on some continental shelves are greater than 10.000%. Because of the shallow nature of the shelf areas, a significant sea-air flux may appear from bottom sediments. Methane production in shallow-water sediments occurs below the sulphate penetration depth. At locations with extremely high sedimentation rates and high primary production sulphate is rapidly depleted and up to 10 % of the total organic matter is consumed via methanogenesis. At other sites it is usually less than 1 %. At many other suspected hydrocarbon seep sites, isolated deep-water coral reef structures are found. It is suspected that sequestration by biological activity (bacteria and archaea) is active here, such that no ebullition of hydrocarbons can be detected. Seeps appear as a complex system with vertical and horizontal shifts in the relative dominance of chemoautotrophic and heterotrophic processes with increasing distance away from the seep. A surprising discovery is the temporal variability of free gas venting and aqueous flux rates. In situ measurements reveal that orders of magnitude in variability occurs at the highest aqueous flux rate sites, with episodes of reduced flow and even flow reversals. Anaerobic oxidation of methane in methane-rich sediments is most probable mediated by a structured consortium of archaea and sulfate-reducing bacteria living in syntrophic association. This consortium may occur in extremely high numbers of 10^10 cells per ml sediment.

Conclusions

- Gas hydrates are possibly of major economic potential as source of methane.
- Anaerobic oxidation of methane in methane-rich sediments is most probable mediated by a structured consortium of archaea and sulfate-reducing bacteria living in syntrophic association hence release of methane to the atmosphere is unlikely in deeper marine basins.
- Major steps forward were made in the imaging and understanding of mounds and pockmarks due to modern sonar measurements and ROV videos.

Forum discussion

During the forum discussion we attempted to summarize some of the findings of the workshop and illustrate some of the controversies still existing. When starting the workshop, we wondered whether seeps would play a role in the global production of methane and in the greenhouse effect and global warming. Although hard figures on emissions rates of hydrocarbons are lacking for most areas affected by seeps, the estimates produced for the South Caspian Basin effectively shows the importance of seep studies in such a framework. However it is also clear that more consorted effort is needed to produce emission rate estimates and to upscale these local estimates to global numbers. There is much activity on offshore seep monitoring despite the fact that these areas are less accessible than seeps onshore. The interest of oil industry in offshore areas of seeps has ensured access to high quality seismic data and the optimized networking of the researchers working on offshore seeps has ensured advancements in this field of science. With the potential of gas hydrates as sources of methane production this efforts has even increased over the past years. The ESF program FLAME proposed to study offshore gas hydrates in the Mediterranean is an example of spin off. The workshop participants all subscribed to the statement that they had seen many new aspects of studies of seeps. The set-up of the workshop being multi-disciplinary and bringing together a wide spectrum of scientists has worked. This has also made clear some discrepancies such as the lack of cohesion between offshore and onshore studies, the lack of integration of surface and subsurface data sets and the lack of global data bases on seeps.

The future direction of the field

The two foremost critical issues in studies of seeps that emerged from the workshop were:

- Quantifying the flux of gas and fluids (mostly methane) from seeps into the atmosphere.
- A strategy for the study of seeps is needed and should include seep detection, characterisation of emission products, quantification of fluxes, study of time variations hence linking seepages mechanisms and tectonics (geology, fault-systems and stress fields).

Increased European collaboration in the field of offshore studies of seeps particularly for gaining a better understanding of gas hydrate provinces in the Mediterranean basin has been proposed under the ESF umbrella with the FLAME proposal. To link with this a network binding scientists that study seeps on the earth land surface in the context of changes in tectonics and local fault mechanics is essential. From our deliberations it has also been clear that emission of gases from seeps in particular the emission of methane is expected to occur on the land surface in areas where seepage is controlled by non-sealed fault systems. In land areas where seepage occurs through the stratigraphy in a near vertical fashion, losses to the atmosphere due to continuous gas diffusion through the cap rock of a reservoir can be considered neglectable. Diffusion through the cap rock is 3 to 4 orders of magnitude less effective than the biodegradation processes in the near surface soil, hence all methane is oxidized prior to reaching the surface. The same is true for offshore seeps in moderate to deep seas.

Here anaerobic oxidation of methane in methane-rich sediments is most probable mediated by a structured consortium of archaea and sulfate-reducing bacteria living in syntrophic association hence release of methane to the atmosphere is unlikely in deeper marine basins. The methane that reaches the surface-water boundary is locally oxidized and dissolved.

We envisage proposing a network to the European Science Foundation that focuses on the study of seeps on land. This network should be concerned with the following aspects:

- Quantifying the flux of gas and fluids (mostly methane) from onshore seeps into the atmosphere.
- Developing strategies for the study of seeps based on detection, characterisation of emission products, quantification of fluxes, study of time variations hence linking seepages mechanisms and tectonics (geology, fault-systems and stress fields).
- Developing methods of integrating surface and subsurface detection techniques.
- Devising ways of upscaling local emission estimates on isolated seep vents to regional and ultimately global production figures.
- Establishing the role of seeps in historic as well as in the geologic history at basin scales.

The proposed network will work in close collaboration with other groups including the FLAME team. The network will use the following instruments:

- Building a database with known seeps, location type aerial extent, historic records of emission etc. and cataloging these on a website on onshore seeps in a systematic manor.
- Organizing joint sessions at the EUG conference.
- Organizing local and thematic workshop in joining countries and on specialized topics
- Organizing field excursions and field measurement campaigns

Statistical Information on the participants

The workshop was attended by 67 delegates (55 male, 12 female) representing 15 countries of which 4 are non-ESF member countries (Israel, Azerbaijan, USA and Canada). There were 5 no-shows, none of which were presenters. Table 1 gives an overview of participants per country. We managed to offer financial support to 24 participants from the ESF grant (7 of which were representing the Netherlands). A grant from Shell provided financial support for 1 USA participant, a grant from the Space Research Organisation of the Netherlands (SRON) provided financial support for 3 participants from Azerbaijan. All other 29 participants were financially self supporting. The full list of participants in given in Annex 1.

Table 1: List of participants per country.

Country	No. participants
Netherlands	37
Czech Rep.	1
France	2
Sweden	1
Germany	5
Norway	4
Belgium	2
Spain	2
Israel	1
USA	1
Italy	1
Canada	1
Azerbaijan	3
UK	3
Turkey	1
unknown	2

Annex 1: Final list of participants

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