The Power of Integrated Solutions Using Both Production Geochemistry and PVT*

Ellie Chuparova[1]

Search and Discovery Article #42480 (2019)**
Posted December 16, 2019

*Adapted from oral presentation given at 2019 AAPG Hedberg Conference, The Evolution of Petroleum Systems Analysis: Changing of the Guard from Late Mature Experts to Peak Generating Staff, Houston, Texas, United States, March 4-6, 2019
 DOI:10.1306/42480Chuparova2019

[1]EC Petroleum Geochemistry Consulting, LLC, Houston, TX, United States (elli26@yahoo.com)

Abstract

Petroleum geochemistry is one of the main petroleum system analysis (PSA) tools and has a proven record of value-added applications along the whole lifecycle of petroleum asset development – from exploration and appraisal to development, production, abandonment and environmental remediation. Reservoir and production geochemistry refers to the applications of petroleum geochemistry mainly during the development and production of an asset. Appraisal is also a very important stage for production geochemistry because the information gathered at that stage defines the static conditions baseline of the reservoir to which the following dynamic production data are compared for many years to come. Reservoir and production geochemistry is one of the more recently developed (late 1980s - early 1990s) applications of petroleum geochemistry to oil and gas business. It utilizes subtle but measurable compositional differences in reservoir fluids (oil, gas, water) that are controlled by two main groups of factors: 1) variations in charge history (e.g., maturity and/or source rock of the fluids accumulating in the reservoir); 2) post- accumulation in-reservoir processes (e.g., biodegradation, leakage, water washing, charge mixing). The advancement of reservoir and production geochemistry clearly showed the need for integration of geochemistry with reservoir characterization, development geology and petroleum engineering, including PVTx (Pressure-Volume- Temperature-Composition). The present talk will discuss how geochemists and engineers apply PVTx, provide a brief historical overview of several concepts related to in-reservoir charge accumulation and alteration processes, and their impact on reservoir fluid properties for conventional reservoirs. Static and dynamic reservoir compartmentalization, compositionally graded columns and depletion, impact of in-reservoir charge mixing processes on reservoir fluid properties, production allocation, solving flow assurance (wax and

asphaltene deposition) and production (well, pipeline leaks, oil spills) problems are some of the main integrated geochemistry-engineering applications to be reviewed. The unconventional oil and gas revolution of the last decade presented new challenges and opportunities for integration of geochemistry with engineering, including integration with drilling and completion engineering. Main applications to be discussed include identification of oil “sweet spots”, fractured/fault zones and reservoir compartments along lateral wells, evaluation of reservoir fluid properties from surface data, time-lapse geochemistry to monitor dynamic changes in stimulated and effective drained reservoir volumes and production allocation.

The Power of Integrated Solutions Using Both Production Geochemistry and PVT

Ellie Chuparova

EC Petroleum Geochemistry Consulting, LLC

Presentation prepared for AAPG Hedberg Research Conference

Houston, TX, March 4-6th, 2019

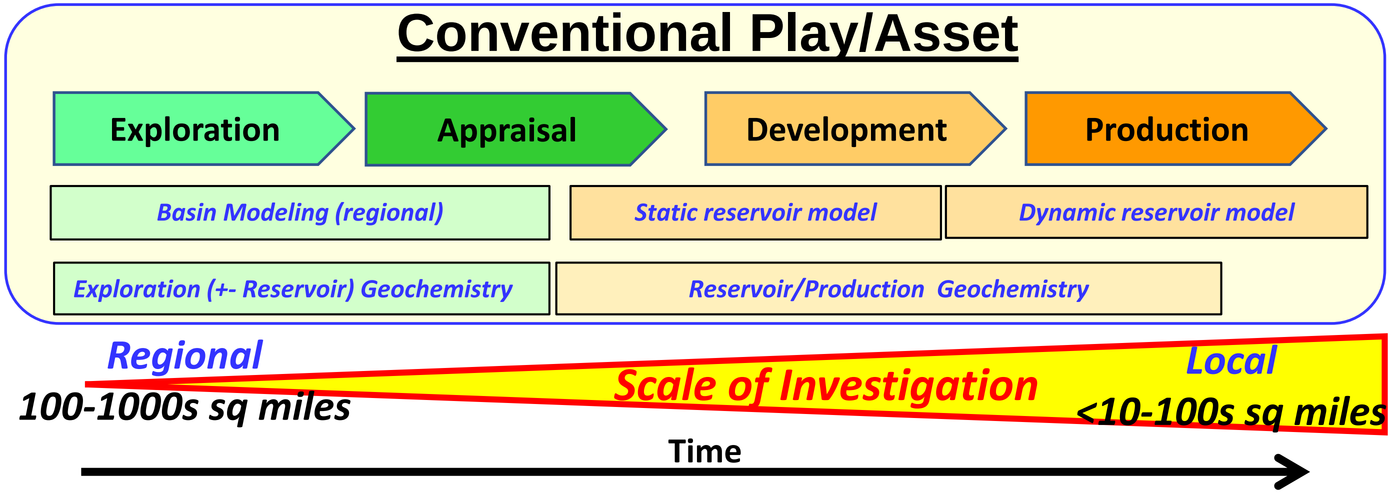
Outline

- **The role of petroleum geochemistry** in an asset lifecycle

- **Basic principles**
  - Reservoir and production geochemistry
  - PVTx and phase behavior

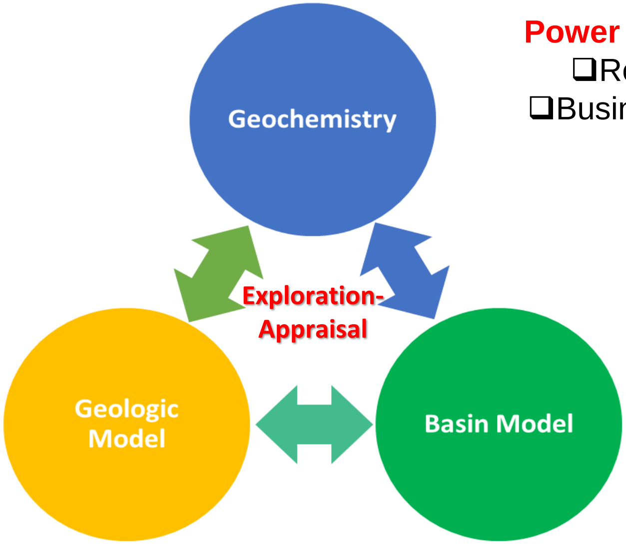
- **Case study examples**
  - Static and dynamic reservoir compartmentalization
  - Compositionally graded fluid columns
  - Unconventionals

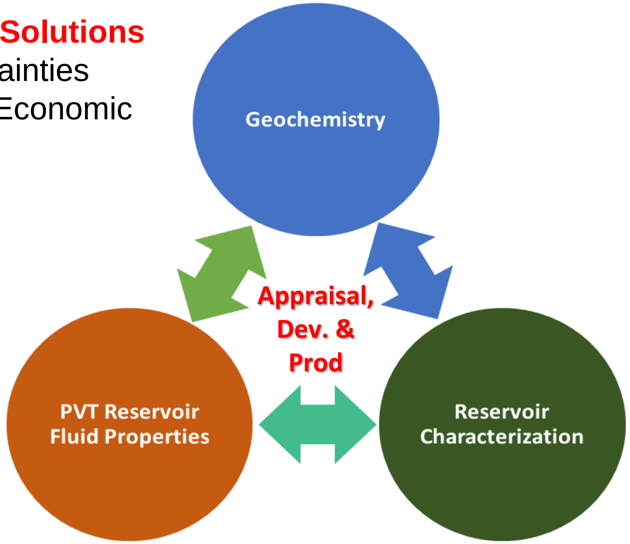
Role of Geochemistry in an Asset Lifecycle



Power of Integrated Solutions

- ❑Reduced Uncertainties
- ❑Business impact = Economic value





Reservoir and Production Geochemistry

Reservoir and production geochemistry evolved during the late 1980s and early 1990s in two complementary trends:

- **Solving problems *on production time-scale*** by using the lateral and vertical variability in reservoir fluid (oil, gas, water) composition and liquid-solid phase transitions (e.g., wax, asphaltene, diamondoids deposition)– *reservoir compartmentalization, production allocation of commingled fluids, operational problems, flow assurance.*

Slentz (1981), Kaufman et al. (1987), Kaufman et al. (1990), del Rio & Philp (1992), Carlson et al (1993), Hwang & Baskin (1994), Hwang & Elsinger (1995), Philp et al. (1995), McCaffrey et al (1996), Nicole et al. (1997)

- **Understanding the control factors on the variability** in reservoir fluid compositional fingerprints ***on a geological time-scale*** prior to production - *charge filling history (source, maturity, migration directions), in-reservoir post-accumulation processes (e.g., biodegradation, water washing, leakage, de-asphalting).*

England et al. (1987), Lafargue & Barker (1988), England (1989), Leythaeuser & Ruckhein (1989), Hwang et al. (1994), Smalley & England (1994, 1996), Larter & Aplin (1995), Larter et al. (1995), Smalley et al. (1995, 1997), Halpern (1995), Huc et al. (1995), Holba et al (1996), Westrich et al. (1996)

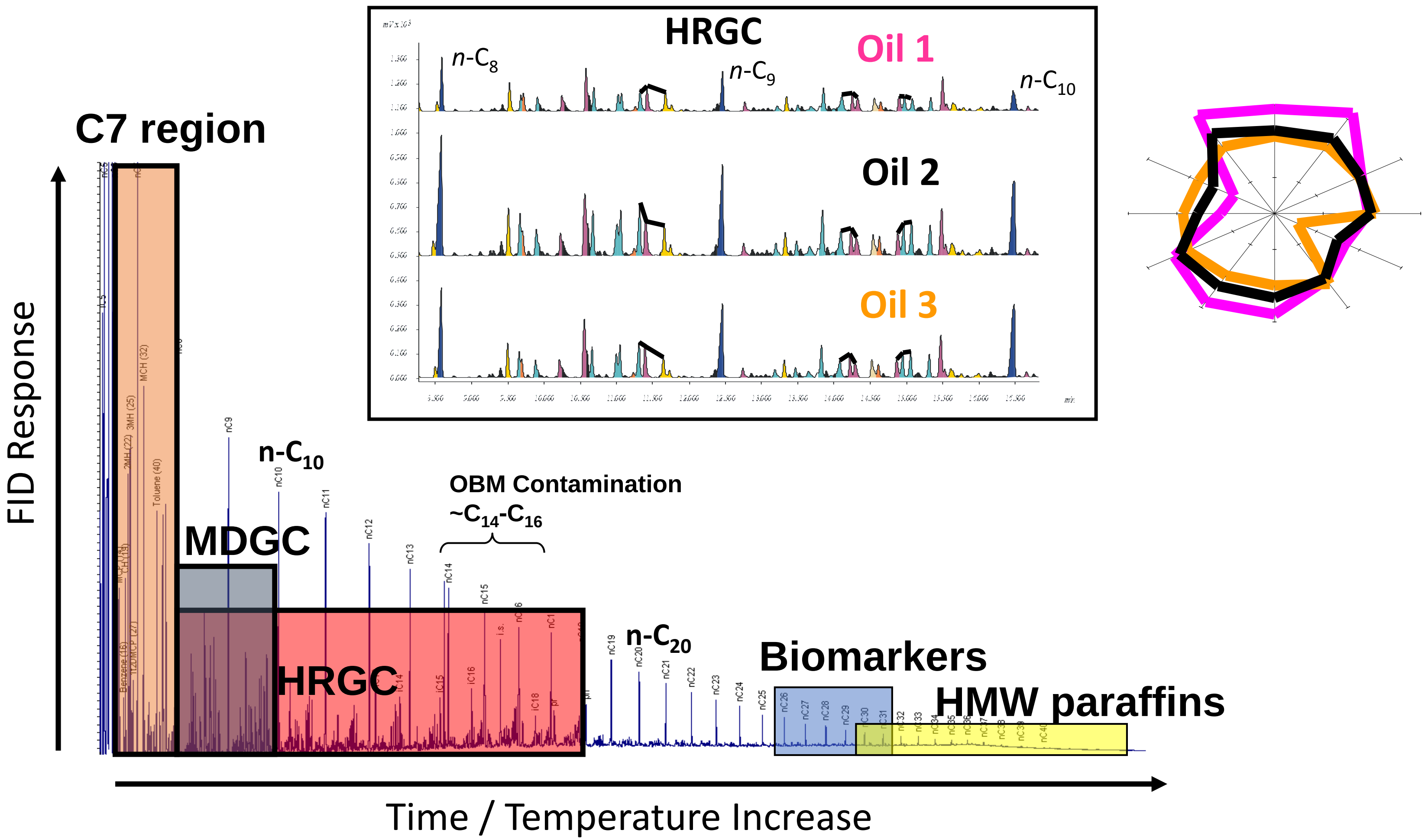
Reservoir Fingerprinting Technology

- **Premise:** Fluids in different reservoir compartments have subtle but detectable geochemical composition differences.

- **Assumption:** Post-accumulation homogenization of HC fluids after filling the trap is rapid. (e.g., Kaufman et al., 1990; Larter and Aplin, 1995; Stainford, 2004)

- **Enablers:** Technological and analytical developments in:
  - High-resolution gas chromatography (HRGC)
  - Multi-dimensional gas chromatography (MDGC)
  - High-temperature gas chromatography (HTGC)
  - Two-dimensional gas chromatography (GCxGC)
  - *In-situ* real time Downhole Fluid Analyzer (DFA) using visible to near-infrared spectroscopy

Reservoir Fingerprinting Technology

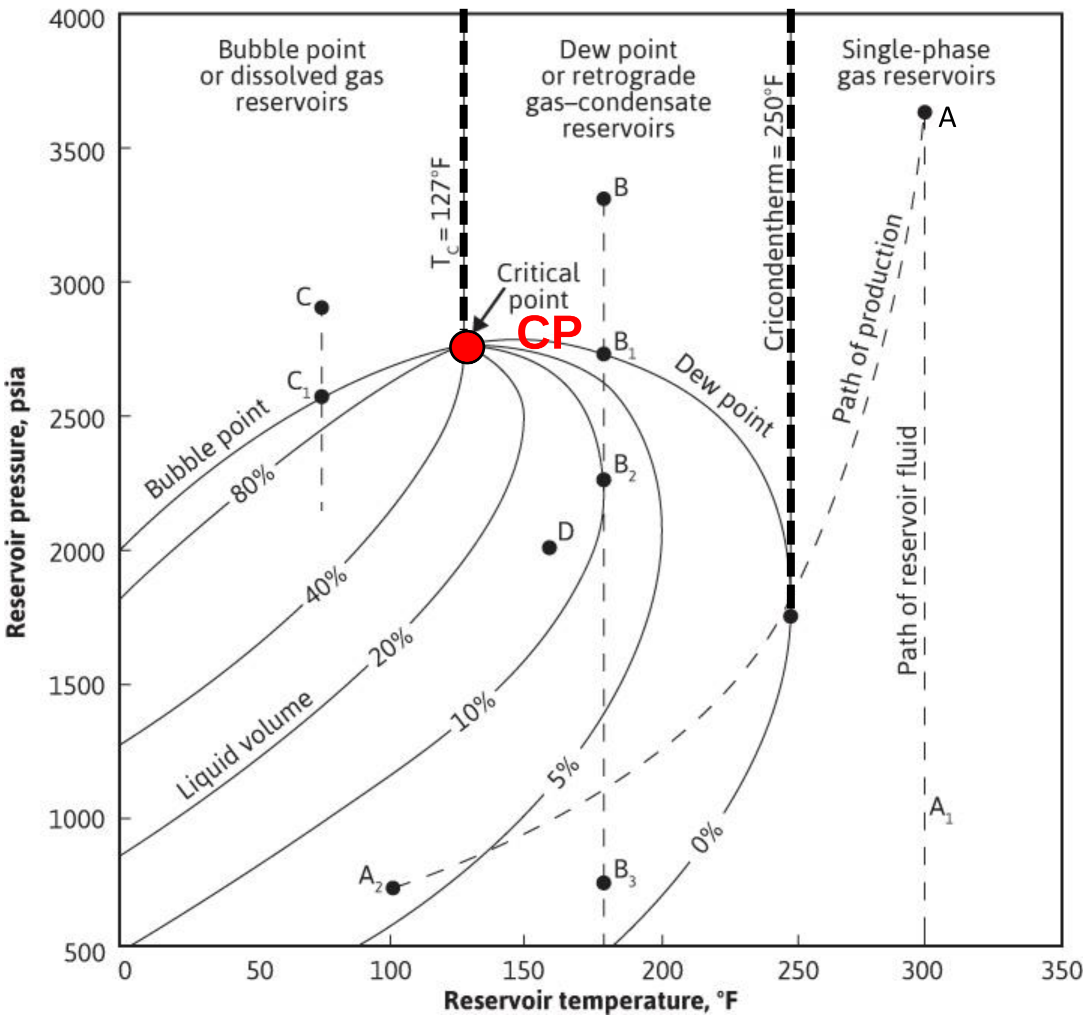


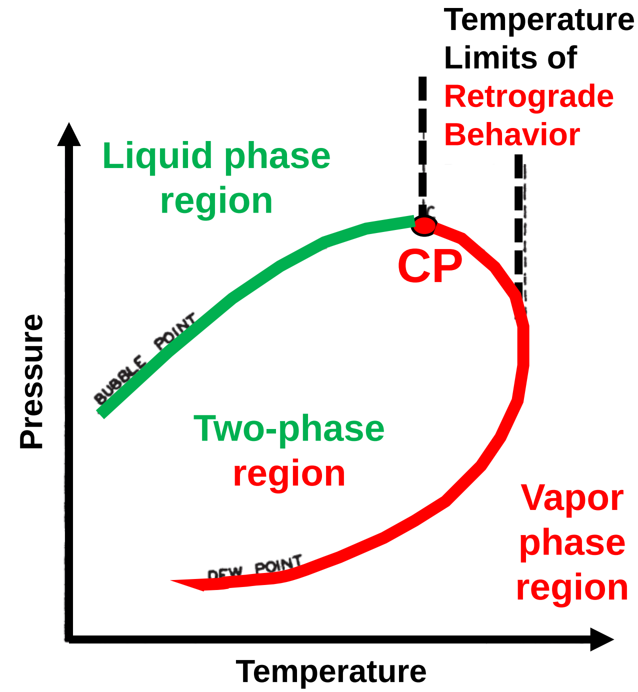
PVTx and Fluid Properties

- **PVTx** = Pressure, Volume, Temperature, X – Composition
- **Fluid properties** (e.g., GOR, density/API Gravity, FVF, reservoir viscosity, P_{sat}, compressibility) are extremely important for a number of ***engineering correlations and applications:***

  – reserve calculations, development strategy (e.g., predict and optimize reservoir performance, manage production rates and well placement, identify unswept reservoir volumes), surface facilities design.
- **Control factors on fluid properties**:
  - **Primary – Petroleum System** – thermal maturity, source rock type and facies, migration
  - **Secondary – In-reservoir post-accumulation processes** – biodegradation, water washing, trap leakage, migration fractionation, charge mixing

Phase Behavior and Classification of Reservoir Fluids





CP = Critical Point

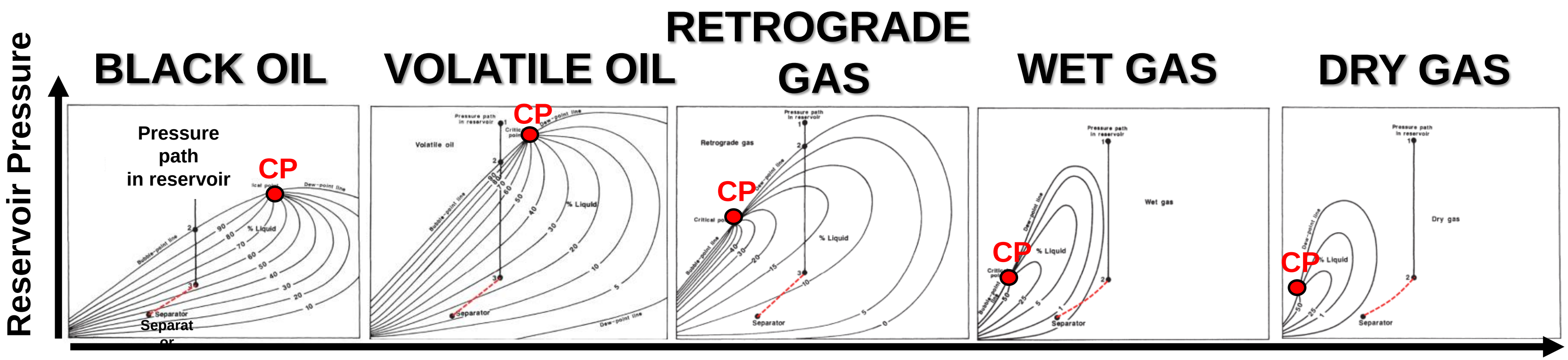
Modified after Terry & Rodgers (2014)

Phase Behavior and Classification of Reservoir Fluids

Classification of Reservoir Fluids using Production Information*

RESERVOIR FLUID TYPE	OIL GRAVITY	INITIAL PRODUCING GOR	COLOR	INITIAL OIL FVF	C7+ IN RES. FLUID
	°API	scf/STB		res bbl/STB	mol %
BLACK OIL	<45	<2000	DARK/BLACK	<2	> 30
VOLATILE OIL (Tcrit>Tres)	>=40	2000-3300	BROWN, ORANGE, GREEN	>2	12.5-30
RETROGRADE GAS (Tcrit<Tres)	40-60	3300 -50,000	LIGHT COLOR, BROWN, GREENISH, WATER-WHITE		<12.5
WET GAS	40-60	>50,000	WATER WHITE		
DRY GAS					

**Reservoir fluid type could be confirmed only by PVT lab experiments (McCain, 1990)*



Reservoir Temperature

Producing GOR and gravity increase as Pres falls below Psat

Condensate drop out in reservoir <Psat

No liquid is formed in the reservoir. Some –at separator. Producing GOR remains constant

No liquid is formed on the surface except some liquid water.

CP = Critical Point

Applications of Petroleum Geochemistry during Development and Production

- Reservoir Compartmentalization
  - Static
  - Dynamic – using time-lapse geochemistry
- Compositionally graded fluid columns
- Operational problems – case leakage
- Production allocation of commingled fluids
- Production surveillance using Time-Lapse Geochemistry
  - Predict water breakthrough during primary depletion or secondary water flood recovery
  - Monitor CO_2 break-through during tertiary recovery
- Flow assurance
  - Wax and asphaltene deposition problems in well equipment and pipelines and their remediation

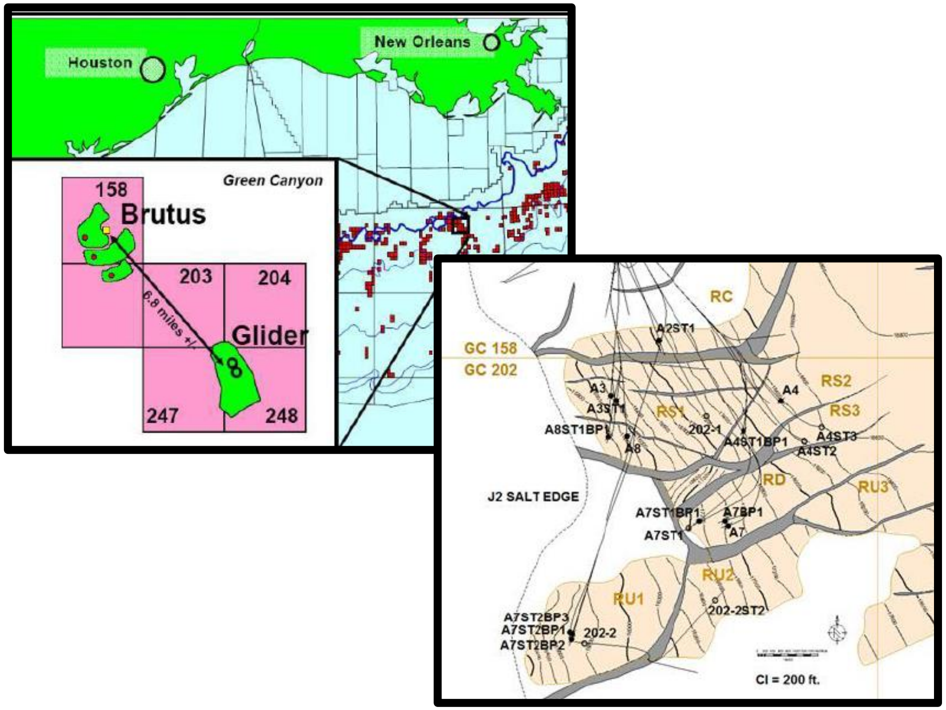
Hwang & Elsinger (1995), Chuparova & Philp (1998), Edman & Burk (1999), Ganz et al. (1999), Hwang et al. (2000), Kaufman et al (2002), Murty et al. (2005), Milkov et al. (2007) , Gelin et al. (2009), Elsinger et al. (2010), McCaffrey et al. (2017), van Bergen & Gordon (2018)

Field Case Studies and Examples

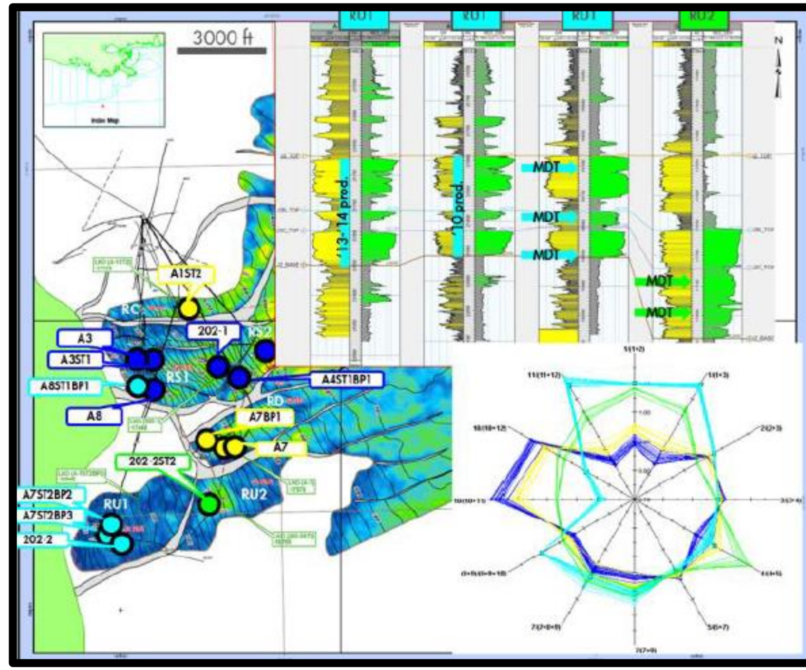
- Static and Dynamic Reservoir Compartmentalization using time-lapse geochemistry

- Compositionally graded fluid columns

Brutus Late Life Redevelopment (DW GOM)



- Can RU2 block oils be drained from the existing wells in RU1 block?
- Are there bypassed volumes of oil in RU2 block?



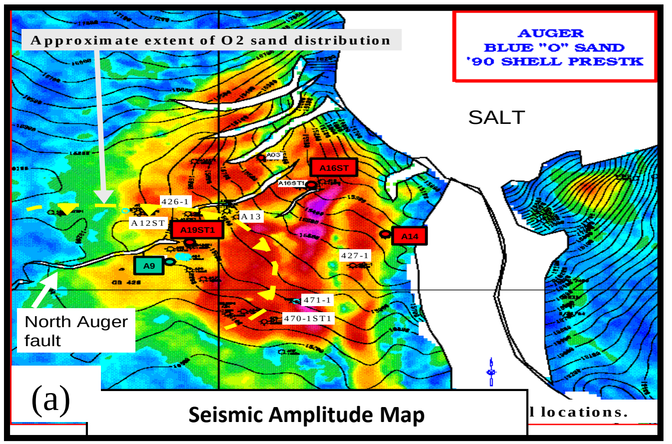
J2 sand structure map with geochemical fingerprinting using C_8-C_{10} alkylbenzenes (MDGC).

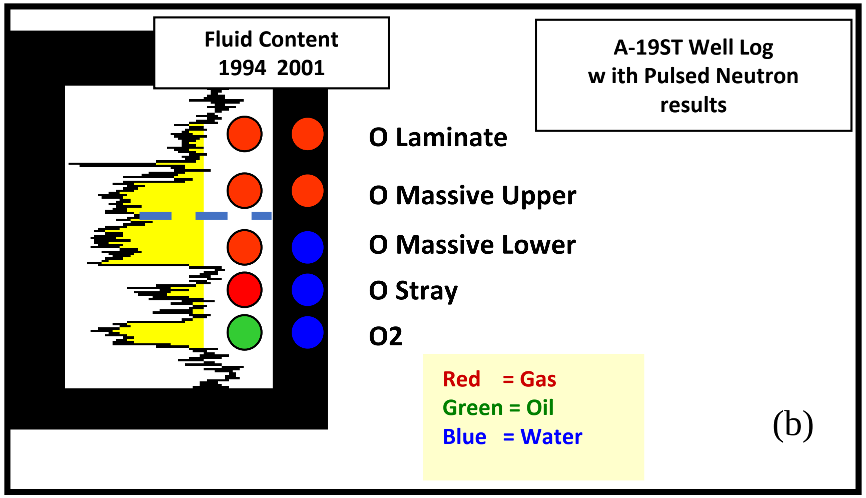
Integrated approach: 4D seismic, geologic model, pre-production pressures, history matching and time-lapse geochemical fingerprinting.

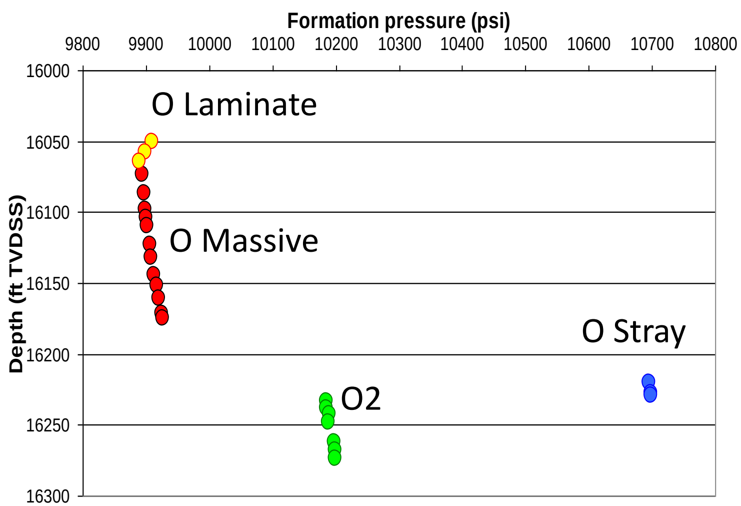
Business impact: Identified bypassed oil volumes in RU2 block for future infill drilling.

Broussard et al. ©2015 SEG New Orleans Annual Meeting

Dynamic Reservoir Compartmentalization, Auger field, DW GOM

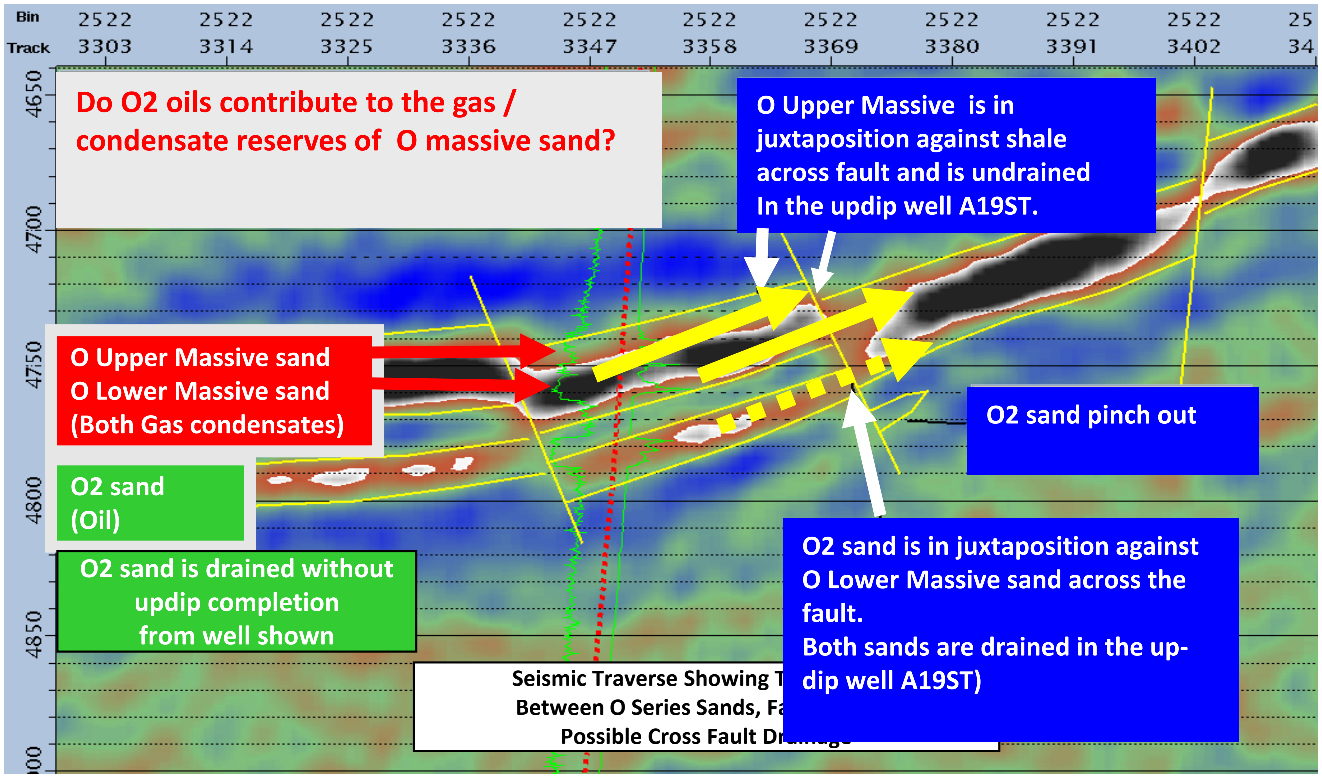






Chuparova et al. In "Reservoir Compartmentalization"
© Geological Society of London Special Publication, vol. 347, 2010

The Geological Hypothesis

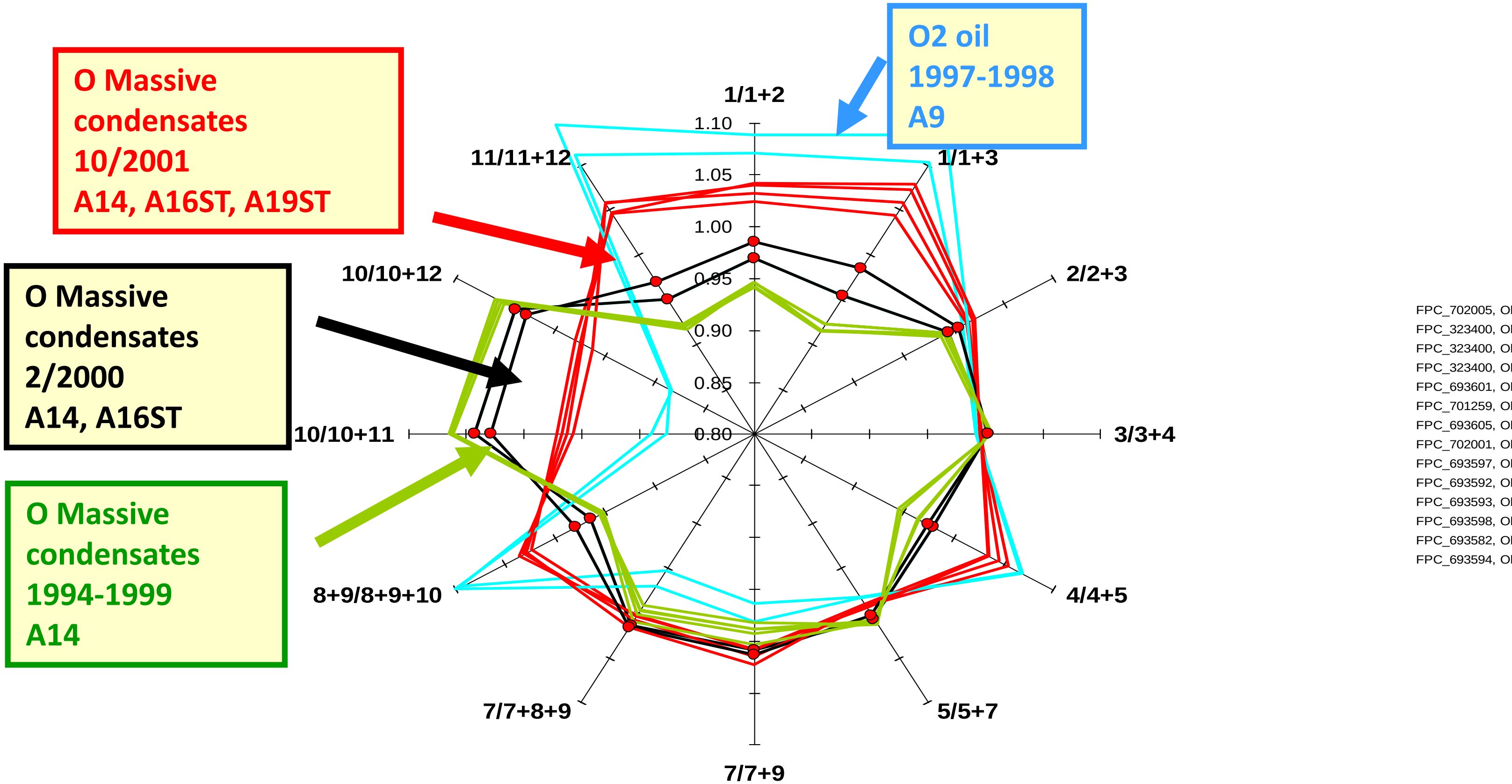


Reservoir Fluid Properties

Date sampling	Well	Sand	Measured Depth (ft)	Sample Source	GOR (scf/bbl)	Tres (F)	Pres (psi)	Psat (psi)	Undersat.
Jul-94	A14	O Mass Blue	17253	surface	3410	176	10540	8000	2540
Jun-97	A13	O Stray Blue	16362	RFT	4012	175	9951	8121	1830
Mar-97	A09	O2 Lower Blue	16356-16410	surface	1032	174	10471	5555	4916

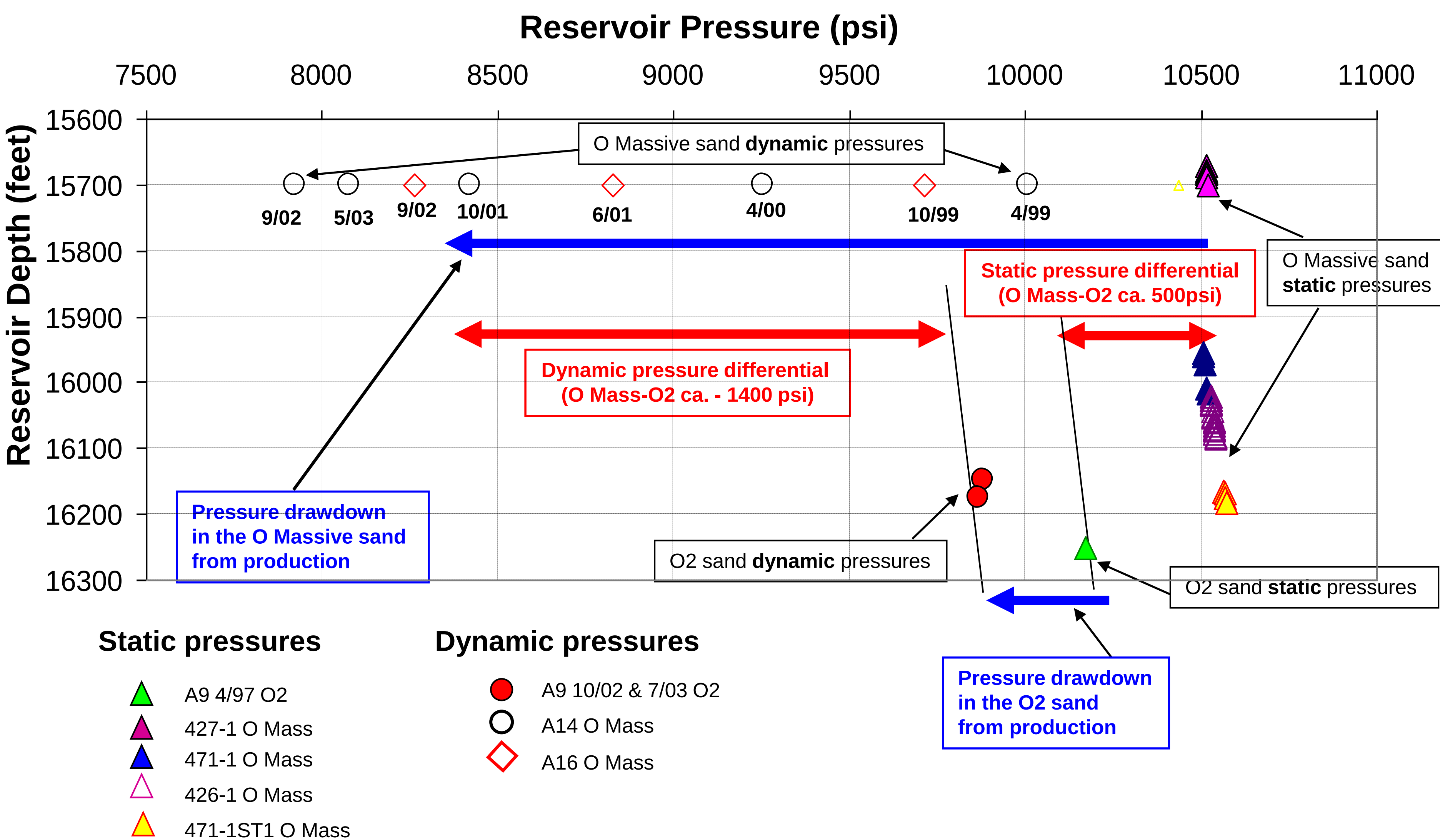
Chuparova et al. In "Reservoir Compartmentalization"
© Geological Society of London Special Publication, vol. 347, 2010

Time-lapse Geochemistry Evidence Strongly Supports the Geological Hypothesis



Chuparova et al. In "Reservoir Compartmentalization"
© Geological Society of London Special Publication, vol. 347, 2010

Static and Dynamic Pressures



Chuparova et al. In "Reservoir Compartmentalization"
© Geological Society of London Special Publication, vol. 347, 2010

Auger Case Study - Summary

- **Integrated approach**:
  - 4D seismic
  - Geologic model
  - 4D production logging (pulsed neutron logs)
  - Pre- and post-production pressure measurements (wireline tools and downhole pressure gauges)
  - PVT
  - Production data
  - Time-lapse geochemistry and fingerprinting

- **Business impact**:
  - Updated static and dynamic reservoirs models
  - Improved field development strategy
  - Improved hydrocarbon recovery efficiency

Chuparova et al. In "Reservoir Compartmentalization"
© Geological Society of London Special Publication, vol. 347, 2010

Additional Examples of Integrated Studies on Dynamic Reservoir Compartmentalization

- **Contribution through baffles between different fault blocks** during production was indicated by identification of static and dynamic reservoir compartments using *integration of the stratigraphic and structural controls on the compartments, seismic, logs, static and dynamic pressures, PVT, production data and geochemistry in Genesis field*, DW GOM (Sweet and Sumpter, 2007; Beeunas et al., 1999).

- **Reservoir fault/baffle breakdown during production** was identified by *time-lapse geochemical fingerprinting in Pierce field, North Sea related to gas injection* in shallower horizons (van Bergen and Gordon, 2018).

- **In contrast, production induced reservoir compartmentalization** due to *faults becoming less leaky* with decreasing reservoir pressure over 100 years of production has been suggested for Elk Hills field, California (Morris et al., 2012)

Compositionally Graded Fluid Columns

- **Continuous reservoir ***
- **Fluid column properties and composition vary**
- **Could lead to false reservoir compartmentalization and production allocation conclusions if not recognized**
- **Could exist under <u>thermodynamic equilibrium or dis-equilibrium conditions</u>**
- **Engineering (EOS) models can't adequately predict main fluid properties (e.g., GOR, API, viscosity) in graded columns under dis-equilibrium conditions– major impact on development decisions and reserve estimates**

A series of dead liquids illustrate the variability of the fluid column in a compositionally graded reservoir

Downdip Updip

GOR, P_{sat} , API, Sat/ Aro INCREASE - Reservoir viscosity DECREASES updip

A. Ranch field, WY (Metcalfe et al., 1988)

** Sage and Lacey (1938): "**<u>Variations in the composition</u>** of the liquid phase of natural reservoirs, which are **<u>continuous</u>** through significant ranges in elevation…"*

Factors controlling compositional grading

1. Gravity

✓Gravitational segregation from density driven convection – heavier components segregate towards the bottom and lighter components towards the top of the column

2. Temperature gradients

✓ Thermal diffusion – segregates lightest components towards the bottom (higher temperatures) and heavier components towards the top of fluid column (lower temperatures)

✓ Thermally induced convection – results in "mixed" fluid systems with close to constant compositions

3. Processes that could cause dis-equilibrium in the fluid column

✓ Dynamic flux of aquifer contacting only part of laterally extensive reservoir could create a sink for continuous depletion of lighter components such as methane

✓ Biodegradation – usually creates lateral and vertical fluid property variation

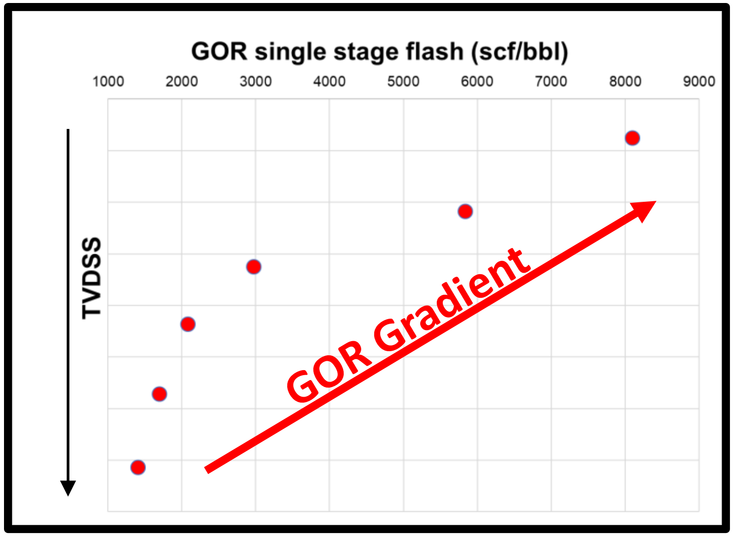
✓ Charge and accumulation history

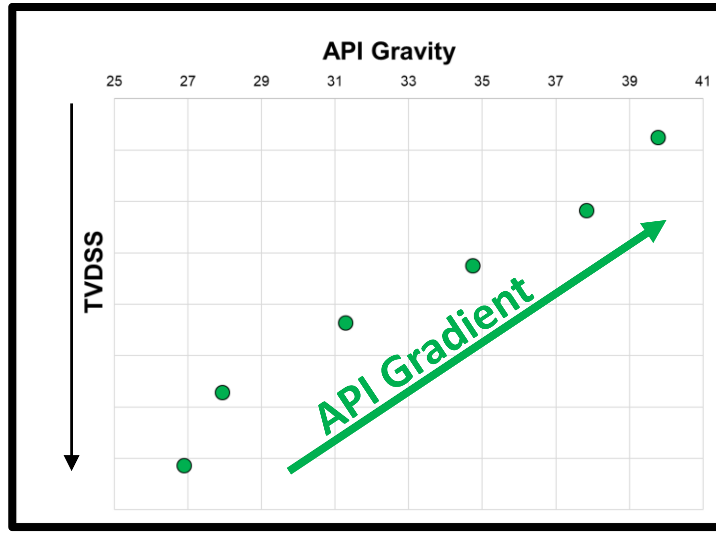
- incomplete charge mixing due to insufficient time since accumulation
- mixing of fluids from multiple charges (e.g., different source rock, maturity)

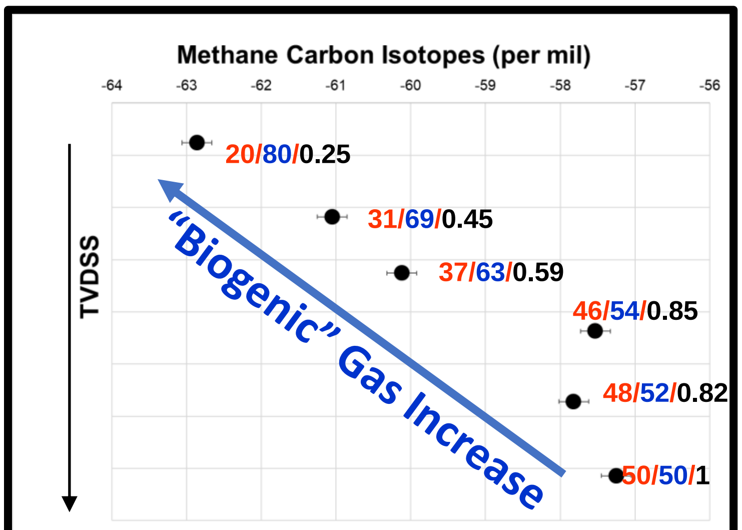
✓ Tar mat, Wax and Asphaltene deposition

Shulte (1980), Hirschberg (1988), Metcalfe et al. (1988), Whitson & Belery (1994), Neveux & Saktikumar (1986), Westrich (1996, 1999), Hoier & Whitson (2000), Ratulowski et al. (2003), Stainford (2004), Weissenberger & Borbas (2004), Ross et al. (2010), Pfeiffer et al. (2011)

Compositionally Graded Column under Dis-equilibrium Conditions





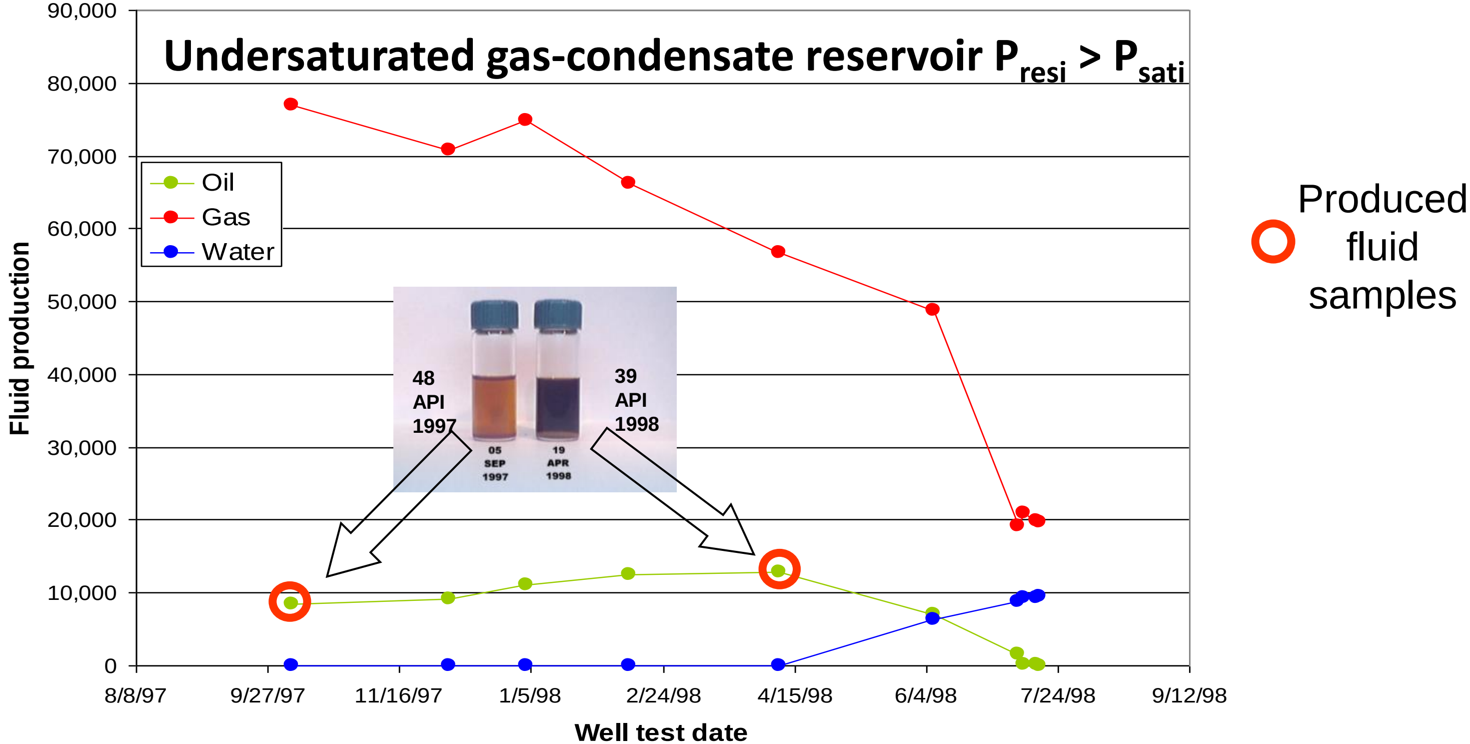


- *Continuous reservoir*
- *GOR gradient range (~1480-8100 scf/bbl)*
- *API Gravity gradient range (~ 27-40 °API)*
- *Gradient in methane carbon isotopes.*
- *Mixing of gases from two sources – thermogenic and "biogenic".*
- *"Biogenic" gas component increases updip*
- *Large gradient in the proportion of "biogenic" and thermogenic gases suggests dis-equilibrium conditions, likely due to insufficient time for mixing in the reservoir.*

20/80/0.25 = Thermogenic gas %/"Biogenic" gas %/ Ratio of thermogenic: biogenic gas

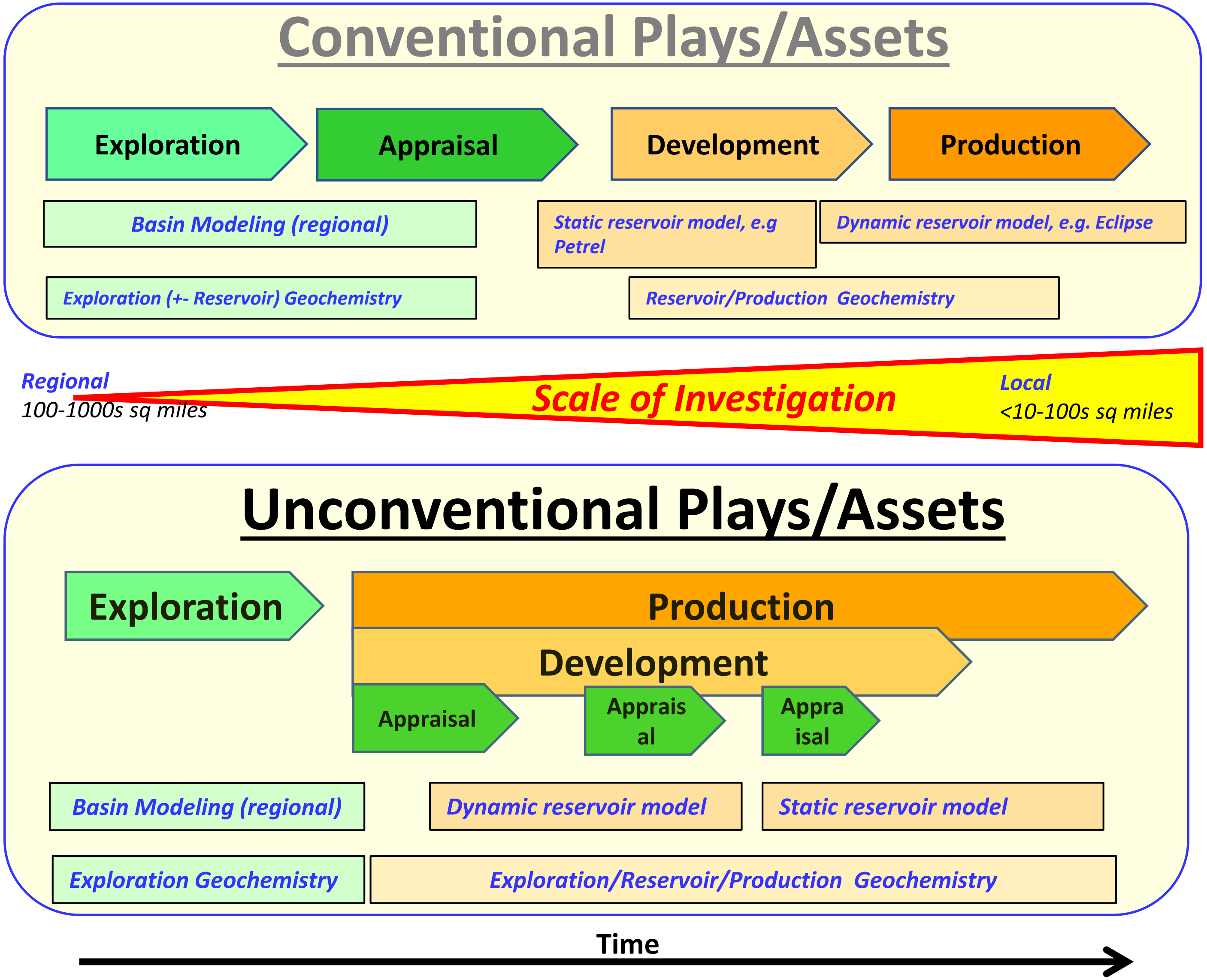
Modified from Zuo et al. (2011)

Depletion of Compositionally Graded Column and Water Breakthrough Prediction



- *Single PVT data point at appraisal.*
- *Time-lapse geochemistry monitoring revealed a dramatic decrease in gravity (9 °API), fluid color, SARA and fingerprints seven months after first production.*
- *The fluid properties’ **change occurred 2 months before the reservoir watered out** and **illustrates a production depletion of a compositionally graded column**.*

Unconventional Play / Assets



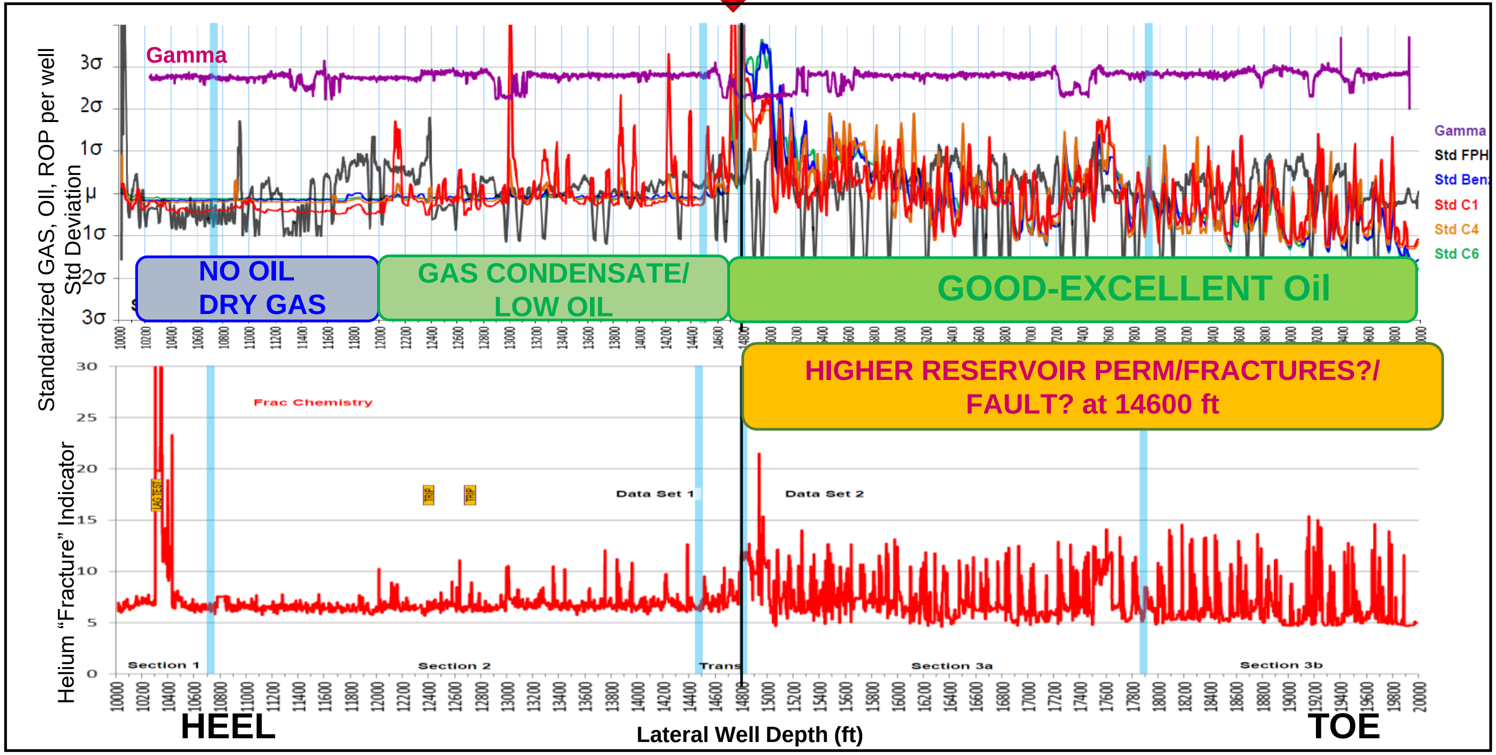
Reservoir and Production Geochemistry Applications for Unconventional Assets

- ❑ Time-lapse geochemistry and production allocation
- ❑ Vertical drainage heights and contribution
- ❑ Finding bypassed oil zones
- ❑ Oil sweet-spot identification and geological targeting
- ❑ High permeability-fracture –fault zones detection along lateral wells
- ❑ Compartments – lateral and vertical
- ❑ Estimate PVT properties from gas and field data
- ❑ Reservoir depletion (e.g., faulting, nearby wells)
- ❑ H_2S origin identification, including induced vs natural
- ❑ Origin of produced waters

Curtis & McBane (1989), Maende & Jarvie (2008), Reed et al. (2010), McCaffrey et al. (2011), Honarpour et al. (2012), Romanoski et al. (2014), Chuparova et al. (2014 a, b), Hohman & Chuparova (2014), Yang et al. (2014), McCaffrey & Baskin (2016), Liu et al (2017), Jweda et al. (2017), Bank & Jokanola (2017)

Permeability Indicators and Reservoir Compartments from Mass Spec Mud Gas Data

12 ft flare; Oil in the shakers while drilling at ~14600 ft

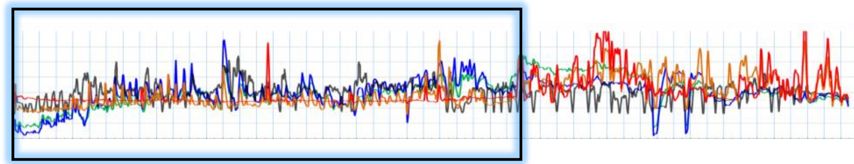


Mass Spec Mud Gas Applications (dq1000)

The studies have *identified, tested and validated* multiple mud gas applications:

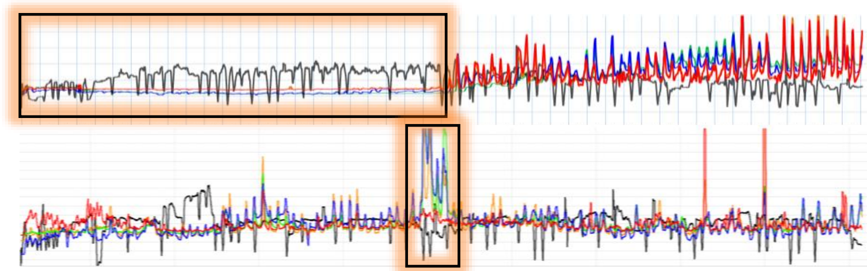
Geologic Targeting

Sweet spot identification

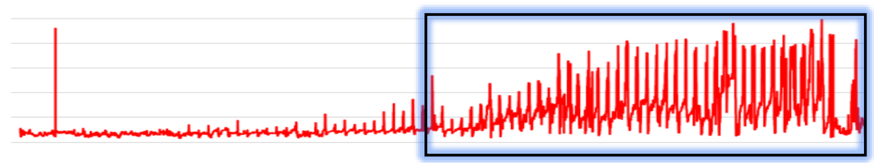


Reservoir Compartments

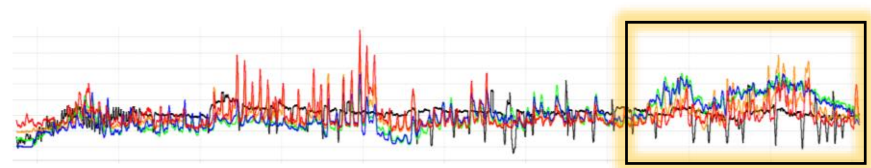
Lateral (stratigraphic)
Vertical (faults)



Permeability Indicators



Reservoir Depletion



Chuparova et al. (2014); Romanoski et al. (2014).
© *2014* AAPG Annual Convention and Exhibition, Houston, Texas, USA, April 6–9, 2014

Concluding Remarks

- ❑ **The power of integrated Geochemistry-PVT solutions** comes from reduced uncertainties, increased business impact and economic value.
- ❑ **Reservoir fluid type always has to be considered** when performing sampling and geochemistry interpretations of fluid samples.
- ❑ **Fluid composition and fluid properties** are Geochemistry-PVT common denominator.
- ❑ **Multi-disciplinary integration** of geochemistry with other geoscience (e.g., geology, seismic, petrophysics) and broader engineering disciplines (e.g., reservoir, drilling, completions) is a powerful approach when working in **unconventional** settings as well.

Acknowledgements

- Professor Roy Knapp (OU-Norman)
- Professor Curtis Whitson (OU-Norman)
- Dr. Naji Nagarajan (Mobil-Exxon-Hess)
- Professor R. Paul Philp (OU-Norman)
- Dr. Joe Westrich (Shell)
- Dr. Birol Dindoruk (Shell)
- Dr. Robert Elsinger (Shell)
- Dr. Alan Kornacki (Shell)

- Session Chairs and Organizers of the 2019 AAPG Hedberg conference

References

- Bang, V., O. A. Jokanola. 2017. Phase predictions using geochemical data. United States Patent application publication No US2017/0075028 A1.
- Beeunas, M.A., T.A. Hudson, J.A. Valley, D. K. Baskin, W.Y. Clark. 1999. Reservoir continuity and architecture of the Genesis field, Gulf of Mexico (Green Canyon 205): an integration of fluid geochemistry with geologic and engineering framework. Gulf Coast Association of Geological Societies Transactions, 49, 90-95.
- van Bergen P.F., M. Gordon. 2018. Production geochemistry: fluids don't lie and the devil is in the detail. In: Application of analytical techniques to petroleum systems, Dowey, P., M. Osborne, H. Vol (eds). Geological Society, London, Special Publication 484.
- Broussard, R., J. Jimenez, E. Leenaart, S. Lyell, J. Stammeijer. 2015. Brutus late life re-development: An integrated field study using legacy 4D seismic and geochemical analysis. SEG New Orleans Annual Meeting, 5333-5337.
- Carlson, R. M. K., S. C. Teerman, J. M. Moldowan, S. R. Jacobson, E. I. Chan, K. S. Dorrough, W. C. Seetoo, B. Mertani. 1993. High temperature gas chromatography of high-wax oils. Proceedings Indonesian Petroleum Association, 22nd Annual Convention, October. 483-504.
- Chouparova E., R. P. Philp. 1998. Geochemical monitoring of waxes and asphaltenes in oils produced during the transition from primary to secondary water flood recovery. Organic Geochemistry 29, 1, 449-461.
- Chuparova, E., T. Kratochvil, J. Kleingeld, P. Bilinski, C. Guillory, J. Bikun, R. Djodjosoeparto. 2010. Integration of time-lapse geochemistry with well logging and seismic to monitor dynamic reservoir fluid communication: Auger field case-study, deep water Gulf of Mexico. In: Reservoir Compartmentalization, Jolley, S. J., Q. J. Fisher, R. B. Ainsworth, P. J. Vrolijk, S. Delisle (eds). Geological Society, London, Special Publication 347, 55-70.
- Chuparova, E. D., A. Romanoski, P. Schmitz, K. McArthur, E. Randall, W. Thompson, I. Harmawan, S. Murray, T. Kisner, R. Pilcher, T. Kirst, J. Courtier. 2014a. An integrated multi-disciplinary approach to mud gas mass spectrometry technology implementation in Bakken/Three Forks unconventional tight light oil play, Williston Basin, North Dakota. AAPG Search and Discovery Article #90189. Presented at AAPG Annual Convention and Exhibition, Houston, Texas, USA, April 6-9, 2014.
- Chuparova, E., J. Hohman, J. Lean. 2014b. Observations of core UV fluorescence of Middle Bakken and Three Forks reservoirs, Williston Basin, North Dakota, Part 2: Integrating with fluid geochemistry to identify producible oil distribution and estimate reserves. AAPG Search and Discovery Article #90189. Presented at AAPG Annual Convention and Exhibition, Houston, Texas, USA, April 6-9, 2014.
- Curtis, J. B., R. A McBane. 1989. Use of geochemistry to improve identification of completion intervals. SPE Formation Evaluation, June 1989, 163-166.

References

- Del Rio, J. C., R. P. Philp. 1992. High molecular weight hydrocarbon (C40) in source rock extracts. AAPG Search and Discovery Article #91015. Presented at AAPG International Conference, Sydney, N.S.W. Australia, August 2-5, 1992.
- Edman, J. D., M. K. Burk. 1999. Geochemistry in an integrated study of reservoir compartmentalization at Ewing Bank 873, offshore Gulf of Mexico. SPE Reservoir Evaluation and Engineering 2, 6, December, 520-526.
- Elsinger, R. J., E. M. H. Leenaarts, J. Kleingeld, P. van Bergen, F. Gelin. 2010. Otter-Eider geochemical production allocation: 6+ years of continuous monitoring to provide fiscal measurements for hydrocarbon accounting. AAPG Hedberg Conference, Vail, Colorado, June 8-11, 2010.
- England, W. A., A. S. Mackenzie, T. M. Quigley, D. M. Mann. 1987. The movement and entrapment of petroleum in the subsurface. J. Geol. Soc. London 144, 233.
- England, W. A. 1990. The organic geochemistry of petroleum reservoirs. Organic Geochemistry 16, 415-425.
- Ganz, H. H., M. Hempton, W. Knowles, F. van der Veen, R. Kreulen. 1999. Integrated reservoir geochemistry: Finding oil by reconstructing migration pathways and paleo oil-water contacts. SPE 56896 presented at the 1999 Offshore Europe Conference, 7-9 September 1999, Aberdeen, UK.
- Gelin, F., F. Montel, J. Bickert, A. Noyau. 2007. Gas condensate allocation in un-mixed complex reservoirs using combined fingerprinting and PVT technologies. International Petroleum Technology Conference, Doha, Qatar, 7-9 December. IPTC 12971.
- Halpern, H. A. 1995. Development and applications of light-hydrocarbon-based star diagrams. AAPG Bull 79, 6, 801-815.
- Hirschberg, A. 1988. Role of asphaltenes in compositional grading of a reservoir's fluid column. SPE paper 13171.
- Hoier, L., C. H. Whitson. 2000. Compositional grading – theory and practice. SPE paper 63085.
- Hohman, J., E. Chuparova. 2014. Observations of UV fluorescence in Middle Bakken, Sanish and Three Forks reservoirs, Williston Basin, North Dakota, Part 1: Leveraging core fluorescence to visualize and estimate oil-in-place. AAPG Search and Discovery Article #90189. Presented at AAPG Annual Convention and Exhibition, Houston, Texas, USA, April 6-9, 2014.
- Holba, A. G., L. I. P. Dzou, J. J. Hickey, S. G. Franks, S. J. May, T. Lenney. 1996. Reservoir geochemistry of South Pass 61 Field, Gulf of Mexico: compositional heterogeneities reflecting filling history and biodegradation. Organic Geochemistry 24, 12, 1179-1198.
- Honarpour, M. M., N. R. Nagarajan, A. Orangi, Z. Yao. 2012. Characterization of critical fluid, rock and rock-fluid properties – impact on reservoir performance of liquid-rich shales. SPE paper 158042.

References

- Huc, A.-Y., B. Carpentier, J. P. Courcy, J. P. Durand, I. Kowalewski, E. Lafargue, C. Magnier, P. Ungerer. 1995. Factors controlling the compositional heterogeneity of light hydrocarbons in petroleum reservoirs. In 17th International Meeting on Organic Geochemistry, Donostia-A San Sebastian, September 4-8th. Proceedings, J. O. Grilmalt, C. Dorronsoro, 362-363.
- Hwang, R. J., D. K. Baskin. 1994. Reservoir connectivity and oil homogeneity in a large-scale reservoir. Middle East Petroleum Geoscience Geo94, 2, 529-541.
- Hwang, R. J., A. S. Ahmed, J. M. Moldowan. 1994. Oil composition variation and reservoir continuity: Unity Field, Sudan. Organic Geochemistry 21, 2, 171-188.
- Hwang, R. J., R. J. Elsinger. 1995. Detecting production tubing leak by time resolved geochemical analysis of oils. ASPE 29478 paper.
- Hwang, R. J., D. K. Baskin, S. C. Teerman. 2000. Allocation of commingled pipeline oils to field production. Organic Geochemistry 31, 1463-1474.
- Jweda, J., E. Michael, O. Jokanola, R. Hofer, V. Parisi. 2017. Optimizing field development strategy using time-lapse geochemistry and production allocation in Eagle Ford. Presented at Unconventional Resources Technology Conference, Austin, Texas, USA, 24-26 July, 2017. URTeC 2671245.
- Kaufmann, R. L., A. S. Ahmed, W. B. Hempkins. 1987. A new technique for the analysis of commingled oils and its application to production allocation calculations. Paper IPA 87-23/21, 16th Annual Indonesian Petro. Assoc., 247-268.
- Kaufmann, R. L., A. S. Ahmed, R. J. Elsinger. 1990. Gas chromatography as a development and production tool for fingerprinting oils from individual reservoirs: applications in the Gulf of Mexico. In: Proceedings of the 9th Annual Research Conference of the Society of Economic Paleontologists and Mineralogists. D. Schumaker, B. F. Perkins (eds). 263-282.
- Kaufman, R. L., H. Dashti, C. S. Kabir, J. M. Pederson, M. S. Moon, R. Quttainah, H. al-Wael. 2002. Characterizing the Greater Burgan Field: Use of geochemistry and oil fingerprinting. SPE Reservoir Evaluation & Engineering, June, 190-196.
- Lafargue, E., C. Barker. 1988. Effects of water washing on crude oil compositions. AAPG Bull. 72, 3, 263-276.
- Larter, S. R., A. C. Aplin. 1995. Reservoir geochemistry: Methods and applications. In: The Geochemistry of Reservoirs, W.A. England and J. Cubitt (eds), Geological Society of London Special Publication 86.
- Larter, S.R., G. Macleod, G. S. Petch, A.C Aplin, C. Smalley, A. Fleet, W. England, N. Goodwin, N. Oxtoby, P. Hall, H. Jensen, B. Carpentier, A. Wilhelms, E. Lafargue, A. Huc, G. McAulay, C. Hughes, C. Curtis. 1995. Reservoir geochemistry as a reservoir appraisal and management tool – An evaluation. AAPG International Conference and Exhibition, September 10-13, Nice, France. AAPG search and Discover #90956.
- Leythaeuser D., J. Ruckheim. 1989. Heterogeneity of oil composition within reservoir as a reflection of accumulation history. Geochimica et Cosmochimica Acta 53, 2119-2123.

References

- Liu F., E. Michael, K. Johansen, D. Brown, J. Allwardt. 2017. Time-lapse geochemistry (TLG) application in unconventional reservoir development. Presented at Unconventional Resources Technology Conference, Austin, Texas, USA, 24-26 July, 2017. URTeC 2670186.
- Maende, A., D. Jarvie. 2008. Finding bypassed or overlooked pay zones using geochemistry techniques. International Petroleum Technology Conference, Kuala Lumpur, 3-5 December, 2008, IPTC 12918.
- McCaffrey, M. A., H. A. Legarre, S. J. Johnson. 1996. Using biomarkers to improve heavy oil reservoir management: An example from the Cymric field, Kern County, California. AAPG Bull 80, 904-919.
- McCaffrey, M. A., D. H. Ohms, M. Werner, C. Stone, D. K. Baskin, B. A. Patterson. 2011. Geochemical allocation of commingled oil production or commingled gas production. SPE paper 144618.
- McCaffrey, M. A., D. K. Baskin. 2016. Applying oil fingerprinting to unconventional reservoirs in the Permian Basin for characterization of frac height and quantification of the contribution of multiple formations to commingled production. Presented at Unconventional Resources Technology Conference, San Antonio, Texas, USA, 1-3 August 2016. URTeC 2460348.
- McCaffrey, M. A., A. Al-Khamiss, M. D. Jensen, D. K. Baskin, C. D. Laughrey, W. M. Rodgers. 2017. Diagnosing production problems in highly deviated wells using oil and gas geochemical fingerprinting. Offshore Technology Conference, Houston, Texas, 1-4 May, 2017. OTC-27617-MS.
- McCain, W. D. 1990. The properties of petroleum fluids. PennWell Books, 548 pages.
- Metcalfe, R. S., J. L. Vogel, R. W. Morris. 1988. Compositional gradients in the Anschutz Ranch East field. SPE Reservoir Engineering, August, 1988, 1025-1032.
- Milkov, A. V., E. Goebel, L. Dzou, D. A. Fisher, A. Kutch, N. McCaslin, D. F. Bergman. 2007. Compartmentalization and time-lapse geochemical reservoir surveillance of the Horn Mountain oil field, deep-water Gulf of Mexico. AAPG Bull. 91, 6, 847-876.
- Morris, A. P., K.J. Smart, D.A. Ferrill, N.E. Reish, P.F. Cowell. 2012. Production-induced fault compartmentalization at Elk Hills field, California. AAPG Bull., 96, 6 1001-1015.
- Murty, Ch. R. K., H. K. Zubari, M. A. Beeunas, and M. McCaffrey. 2005. Fluid transfer mechanism using geochemistry in shallow oil zones of Bahrain field: Proceedings of the 14th Society of Petroleum Engineers Middle East Oil and Gas Show and Conference, Bahrain International Exhibition Centre, Bahrain, March 12–15, 2005, SPE Paper 93465.
- Neveux, A. R., A. Sakthikumar, J. M. Nolray. 1988. Delineation and evaluation of a North Sea reservoir containing near-critical fluids. SPE Reservoir Engineering, August 1988, 842-848.
- Nicole, G. C. Boibien, H. L. Ten-Haven, E. Tegelaar, Ph. Chavagnac. 1997. Geochemistry: A powerful tool for reservoir monitoring. SPE paper 37804.

References

- Pfeiffer, T., Z. Reza, W. D. McCain, D. Schechter, O. C. Mullins. 2011. Determination of fluid composition equilibrium – a substantially superior way to assess reservoir connectivity than formation pressure surveys. SPWLA 52nd annual Logging Symposium, May 14-18, 2011.
- Philp, R. P., A. Bishop., J.-C. del Rio, J. Allen. 1995. Characterization of high-molecular weight hydrocarbons (>C40) in oils and reservoir rocks. In The Geochemistry of Reservoirs (Edited by J. M. Cubitt and W. A. England). Geological Society Special Publication 86, 71-85.
- Ratulowski, J., A. N. Fuex, J. T. Westrich, J. J. Sieler. 2003. Theoretical and experimental investigation of isothermal compositional grading. SPE Reservoir Evaluation & Engineering, June 2003, 168-175.
- Reed, J. D., K. Ferworn, S. Brown, J. Zumberge. 2010. Hydrocarbon phase prediction in unconventional resource plays using geochemical and PVT data. AAPG Hedberg Conference, December 5-10, 2010, Austin, Texas, AAPG Search and Discovery article # 90122.
- Romanoski, A., E. Chuparova, C. Jacobs, D. Adam Porath, J. Hohman, B. Warren. 2014. Subsurface characterization of the Bakken/Three Forks unconventional tight oil reservoirs, Williston Basin, North Dakota through the use of high-resolution mud gas mass spectrometry. AAPG Search and Discovery Article #90189. Presented at AAPG Annual Convention and Exhibition, Houston, Texas, USA, April 6-9, 2014.
- Ross, A. S., P. Farrimond, M. Erdmann, S. R. Larter. 2010. Geochemical compositional gradients in a mixed oil reservoir indicative of ongoing biodegradation. Organic Geochemistry 41, 307-320.
- Sage, B. H., W. N. Lacey. 1938. Gravitational concentration gradients in static columns of hydrocarbon fluids. SPE paper 939120-G.
- Shulte, A. M. 1980. Compositional variations within a hydrocarbon column due to gravity. SPE paper 9235.
- Slentz, L. W. 1981. Geochemistry of reservoir fluids as a unique approach to optimum reservoir management. SPE paper 9582.
- Smalley, P. G., W. A. England. 1994. Reservoir compartmentalization assessed with fluid compositional data. SPE Reservoir Engineering, August. 175-180.
- Smalley, P. C., T.A. Dodd, I.L. Stockden, A. Raheim, E.W. Mearns. 1995. Compositional heterogeneities in oilfield formation waters: identifying them using them. In: The Geochemistry of reservoirs, Cubitt J.M., W.A. England (eds). Geological Society, London, Special Publication 86, 59-70.
- Smalley P.C., N.S. Goodwin, J.F. Dillon, C.R. Bidinger, R. J. Drozd. 1997. New tools target oil-quality sweet spots in viscous-oil accumulations. SPE Reservoir Engineering, August, 1997, 157-161.
- Stainford, J. G. 2004. New insights into reservoir filling and mixing processes. In: Understanding Petroleum Reservoirs: Towards and Integrated Reservoir Engineering and Geochemical approach, Cubitt, J. M., England, W. A., Larter, S. (eds). Geological Society, London, Special Publication 237, 115-132.

References

- Sweet, M.L., L.T. Sumpter. 2007. Genesis field, Gulf of Mexico: Recognizing reservoir compartments on geologic and production time scales in deep-water reservoirs. AAPG Bull. 91, 12, 1701-1729.
- Terry, R.E., J. B. Rogers. 2014. Applied petroleum reservoir engineering. Prentice Hall, 3rd edition. 528 pages.
- Weissenburger, K. S., T. Borbas. 2004. Fluid properties, phase and compartmentalization: Magnolia field case-study, deepwater Gulf of Mexico, USA. In: Understanding petroleum reservoirs: Towards and integrated reservoir engineering and geochemical approach, Cubitt, J. M., W. A. England, S. Larter (eds). Geological Society, London, Special Publication 237, 231-256.
- Westrich, J. T., P. O. Knigge, A. N. Fuex, H. I. Halpern. 1996. Evaluating reservoir architecture in the northern Gulf of Mexico using oil and gas chemistry. SPE paper 36541.
- Westrich, J. T., N. Fuex, P. M. O'Neal, H. I. Halpern. 1999. Evaluating reservoir architecture in the Northern Gulf of Mexico with oil and gas geochemistry. SPE paper 59518.
- Whitson, C. H., P. Belery. 1994. Compositional gradients in petroleum reservoirs. SPE paper 28000.
- Yang, T., R. Basquet, A. Callejon, J. J. van Roosmalen, B. Bartusiak. 2014. Shale PVT estimation based on readily available field data. Presented at Unconventional Resources Technology Conference, Denver, Colorado, USA, 25-27 August 2014. URTeC 1884129.
- Zuo, J. Y., H. Elshahawi, C. Dong, A.S. Latifzai, D. Zhang, O. Mullins. 2011. DFA asphaltene gradients for assessing connectivity in reservoirs under active gas charging. SPE paper 145438.