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Combining Advanced Mud-Gas And Rock-Fluid Analysis To Aid Exploration And Development In Unconventional Plays

Introduction:

Although unconventional oil and gas plays are highly variable in terms of geology, geochemistry and structure, many of the key factors within these disciplines are repetitively quoted as influencing successful exploitation. These include:

1) Composition and quality of the *in situ* petroleum fluid(s),
2) Controls on distribution and volume of petroleum, both geographically and within a given borehole,
3) Water saturation and potential for internal or external water production,
4) Rock type and mineralogical composition for log calculations, lateral location and completion optimization,
5) Natural fracture distribution and porosity types,
6) Compartmentalization, sealing and natural interconnectivity, and
7) Relative proportions of locally generated and migrated petroleum.

These factors and other aspects of unconventional petroleum systems can be evaluated before, during or even instead of expensive logging programs using the unavoidable byproducts of the drilling process: namely, borehole gas and drill cuttings. Industry perception of the value of these has waxed and waned over the years due, in part, to variable data quality as well as cost. Use of more advanced geochemical techniques is currently enjoying resurgence (partly the result of the evolution of field ruggedized instrumentation and more reliable analytical techniques) and is paying dividends for those companies that elect to implement them during evaluation of unconventional plays. Of these technologies, the complementary combination of

1) advanced mud-gas analysis in the field using gas-chromatography (GC), mass spectrometry (MS) or GC coupled with MS, and 2) comprehensive cuttings analysis for trapped fluids and elemental or mineralogical content in the lab is one of the most promising new methodologies. As many unconventional resources have a significant number of historical vertical penetrations, rock-fluid databases can be established rapidly and cost-effectively at an early stage without drilling new wells using small quantities of readily available archived cuttings.

Advanced Mud-Gas Analysis:

Recent developments in application of membrane-GC, GCMS and direct MS analysis to mud gas, along with improvements in mud-gas extraction instrumentation and techniques (e.g., constant volume, constant temperature, gas-in and gas-out arrangements) provide data sets that are substantially more robust and detailed than historical Hot-Wire/GC methods. Of these new techniques, direct quadrupole mass spectrometry (DQMS) is by far the most comprehensive, sensitive and flexible tool for compositional evaluation of formation fluids in near real time. DQMS evaluates C_1-C_{10} petroleum species and inorganic compounds such as carbon dioxide, helium, hydrogen, atmospheric gasses (e.g., N_2) and sulfur-bearing volatiles. It can discriminate among the major classes of volatile organic compounds (paraffins, naphthenes, aromatics) as well as contributions from the drilling fluid. Evaluation of such a broad range of chemical compounds allows for unsurpassed chemical fingerprinting. Additionally, a number of inorganic/organic species combinations are indicative of specific subsurface processes. For example, soluble aromatics and organic acids have been found to be indicative of water saturation within charged reservoirs or water legs that are proximal to oil or wet gas accumulations (Barth, 1991; Burtell and Jones, 1996; Zhang et al., 2005). Helium, among other gasses, has been used to evaluate gas-oil contacts and predict distance from that contact in horizontal wells (Turich et al., 2010).

The DQMS instrumentation is uniquely suited for organic-base mud systems, which typically hamper data analysis from other devices, and works in low-pressure reservoirs where conventional equipment is ineffective. Within unconventional plays, DQMS has been used to distinguish among producible hydrocarbon fluid types, identify lower quality or residual accumulations, evaluate potential for water production, assess compartmentalization, and recognize fractures and faults (see below). These data have been used to optimize completions for less costly and better producing wells allowing some operators to rethink and minimize logging runs. Monitoring drilling-generated hydrogen can serve as an early warning for bit wear, failing down-hole motors and general friction in the drill string. Where utilized, this specific application has tangibly contributed to lower drilling costs (Hall and Sterner, 2012).

Comprehensive Cuttings Elemental-Fluid Analysis:

A new procedure for cuttings or core analysis in the lab has been developed during which the rock is first photographed under visible and UV light, then crushed and analyzed for included hydrocarbon and non-hydrocarbon species with a sensitive mass spectrometry system, and finally probed for its elemental composition with a customized X-ray fluorescence (XRF) analyzer. A key aspect of the process is that all analyses are conducted on the same 0.4 gm rock sample with an automated system, thus preserving interrelationships among rock type, fluid type and rock chemistry. Automation and rapid analytical cycles allow collection of large data sets and encourages analysis of entire wellbores from first returns to TD. Individually the techniques are useful; but together they 1) provide unique insights into controls on hydrocarbon, reservoir and pay distribution, 2) represent an additional tool for well placement, and 3) allow organized archival of rock type, fluid and rock chemistry information that is easily retrieved and studied in the context of future wells, even in the absence of the original rock material. Of interest is that these analyses can be performed on historical samples of any age and drilled with any mud/bit type.

Cuttings volatile data are used for a variety of purposes, but the most practical applications to unconventional reservoirs are ultimately aimed at predicting fluid type, composition, quality and volume in tight rock, as well as identifying variability along laterals that can be exploited for more effective completions (Hall, 2008; Hall et al, 1997; Munz, 2001). XRF data of more than 30 major, minor and trace elements in large cuttings sample sets from vertical and horizontal wells can be used with the high resolution sample images and/or spot petrography to document lithology and cements; produce chemical stratigraphic profiles in otherwise monotonous sections; establish depositional environments, facies and provenance; and provide some information relevant to rock behavior during completion activities (Butcher, 2008; Hildred and Rice, 2012; Marsala et al, 2011; Ratcliffe, et al, 2012; Wright et al, 2010). Type profiles through vertical penetrations can be used to help optimize lateral placement and retrospectively establish borehole trajectory in horizontal wells. Finally, white light and UV images provide grain scale details that can be correlated with other data sets to provide a more integrated understanding of what is controlling hydrocarbon and porosity distribution in the reservoir as well as general formation recognition, evaluation of cuttings quality (and implied drilling conditions), and presence of additives that may affect other analyses. UV images indicate specific mineral or kerogen fluorescence that can be correlated with cement or rock types that are difficult to recognize under white light. Kerogen fluorescence color can be related to maturity,

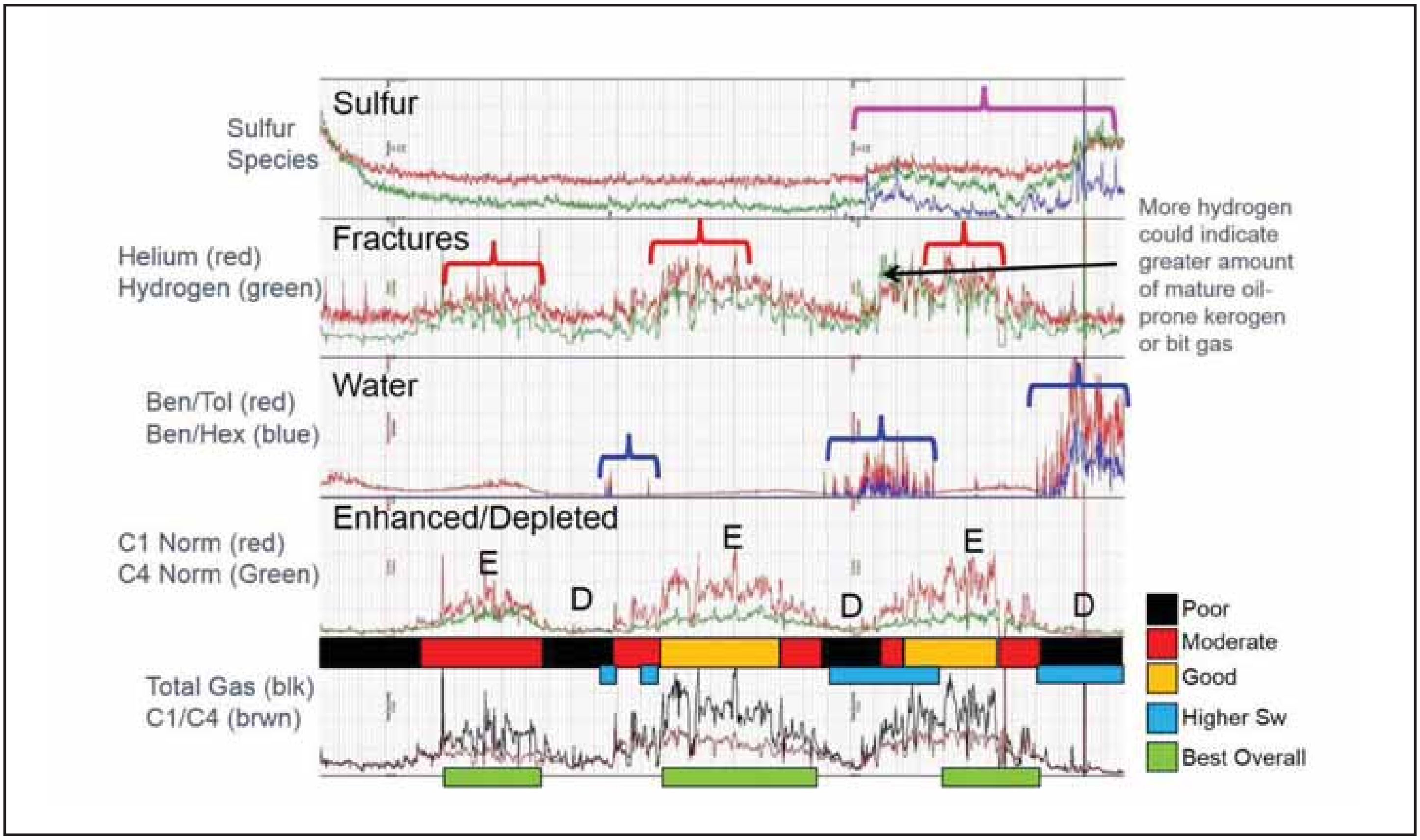

Figure 1. Direct Quadrupole Mass Spectrometry (DQMS) of organic and inorganic volatile species for completion considerations.

at least semi-quantitatively (Lo, 1987). Archived images are much easier to manage than the samples themselves, persist when samples are no longer available and allow geologists to look at the rocks at their desks without relying on sample descriptions or lower quality images from the well site.

Example 1: DQMS to Aid Completion:

Figure 1 illustrates selected DQMS data from a horizontal wellbore within shale. Three main gas-bearing zones are documented as is illustrated by the Total Gas, Helium, C1 Norm and C4 Norm curves (green bars, red brackets, "E" intervals, red and orange bars, respectively). The most producible intervals in the well, based on gas volume and porosity, are indicated where helium is high and separation is recorded between the C1 Norm and C4 Norm curves as a result of natural chromatographic separation of light species in tight rock. In other words, the fractured or otherwise more porous sections of the reservoir concentrate the mobile species, which are weighted toward small molecules like methane and helium. These zones are referred to as "enhanced", while "depleted" zones occur where light/heavy ratios are low (labeled "D" in Fig. 1). Among other possibilities, depleted zones may indicate that gas has been dissipated via through-going fractures. The toe of the wellbore contains higher concentrations of sulfur which may represent an undesirable component of the produced fluid and is known to be present in this particular area (pink bracket). Of equal interest is the distribution of water, which is indicated by the ratios of benzene to toluene and benzene to hexane (blue brackets and bars). These increase in elevated water-saturated intervals because benzene is more soluble in water than toluene and hexane. Considering all of these data allows one to evaluate the most prospective parts of the lateral based on gas composition, gas quality, deliverability and potential for water production. These intervals are indicated by the green bars at the bottom of the diagram. Availability of this extensive data set based solely on mud gas represents a dramatic improvement over conventional approaches and is particularly valuable in horizontal wells where log suites may be minimal.

Example 2: FIS for Early Prediction of Production:

A simple example of using cuttings volatile analysis to anticipate and rank eventual production in unconventional reservoirs is shown in Figures 2 and 3. In Figure 2, cuttings methane concentrations (calibrated millivolt responses from the mass spectrometer) from the horizontal portions

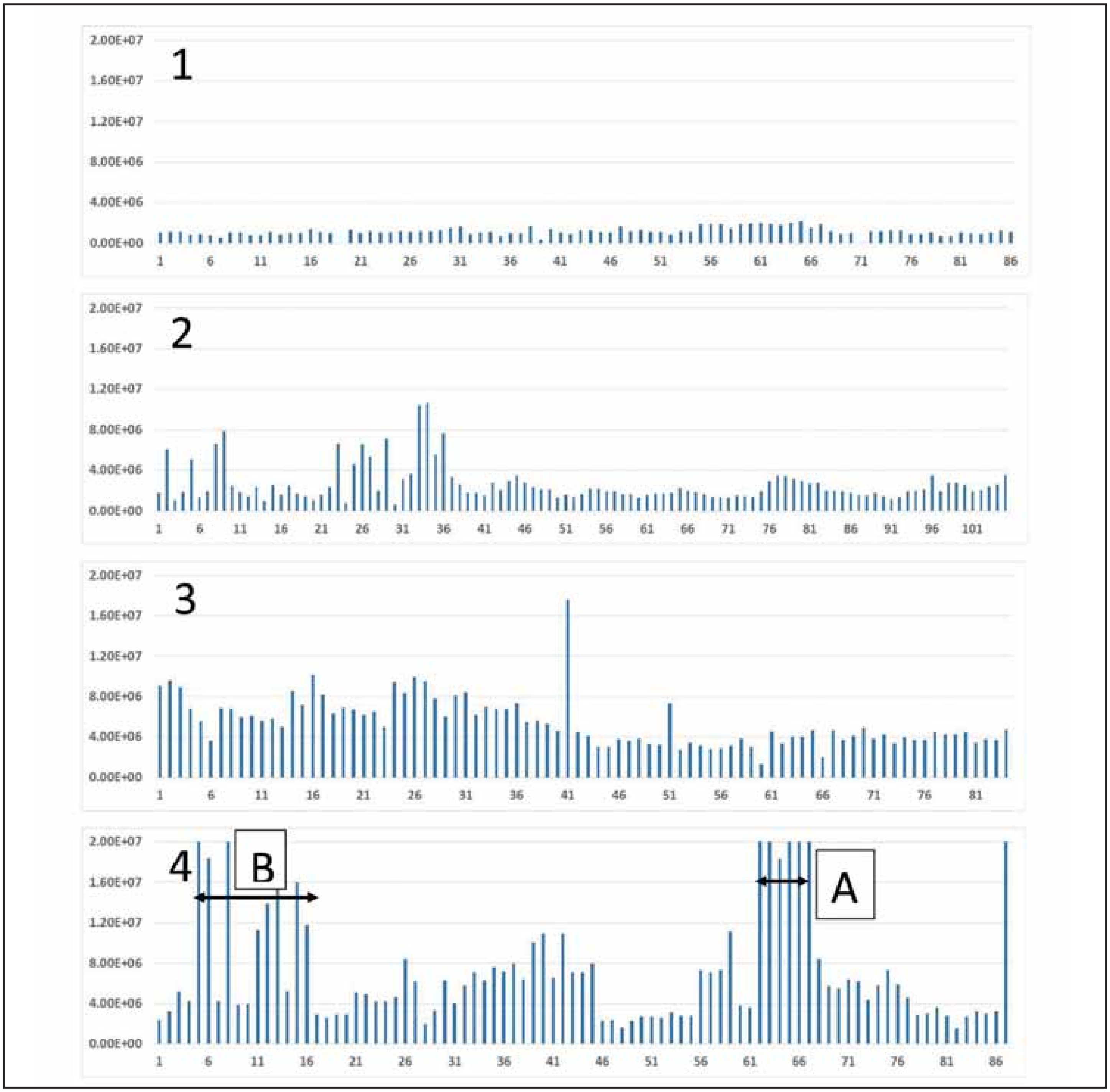

Figure 2. Fluid Inclusion Methane (FIS) response vs. Sample Number of horizontal segments of geographically proximal wells.

of four lateral wells drilled into the same formation within a geographically restricted area are shown as a function of sample number. Data suggest the wells are different in terms of average response as well as variability through the lateral. Figure 3 illustrates the summed Fluid Inclusion Stratigraphy (FIS) response (divided by 10e6 for convenience) vs. average stabilized daily production over a two-month period. Clearly, the eventual relative production from these wells could have been anticipated immediately after drilling, and actual production statistics from future wells in the area can be reasonably pre-

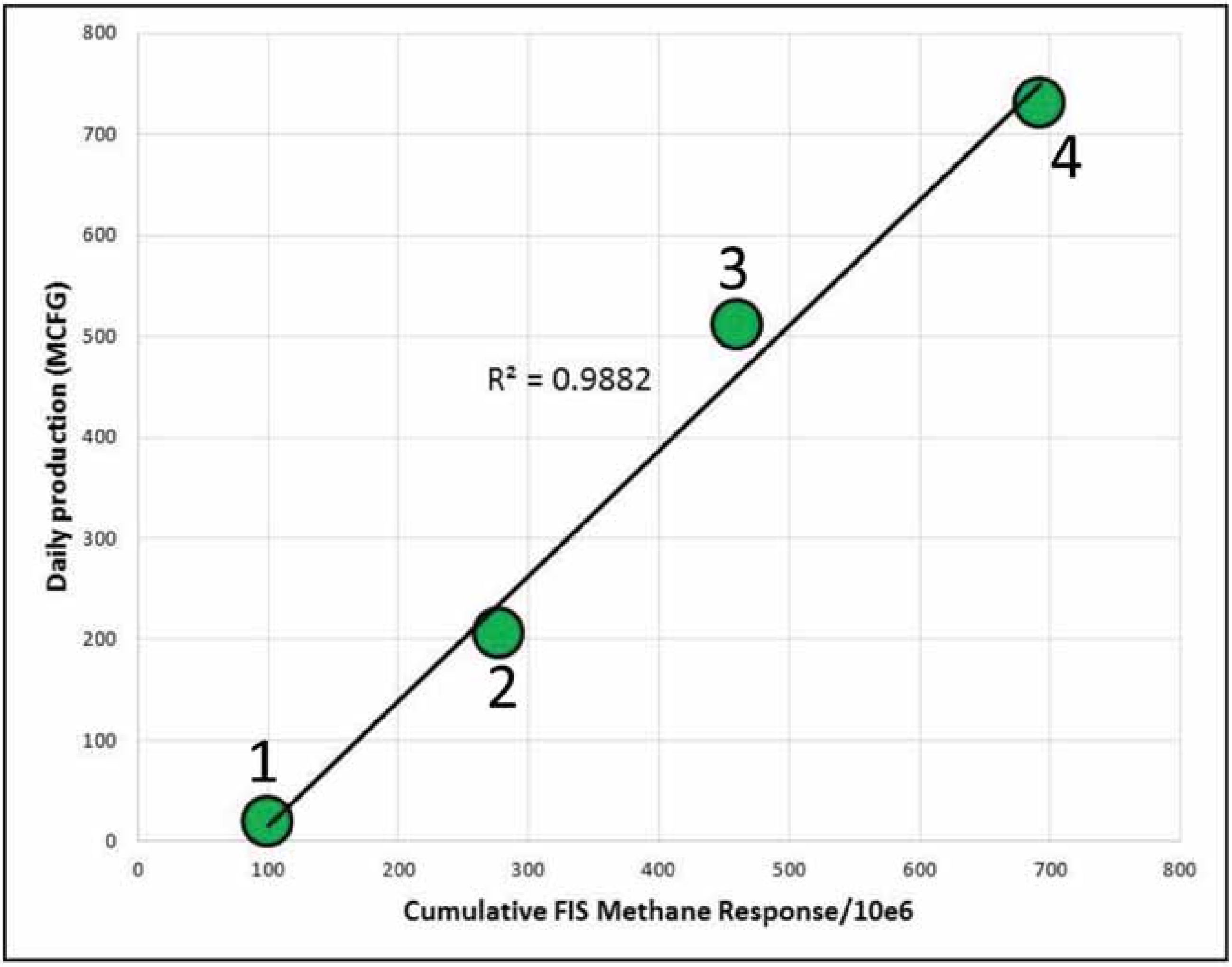

Figure 3. Average Cuttings Methane Response vs. Daily Production for the same four horizontal wells shown in Figure 2.

dicted from the FIS data. Furthermore, contributions to the total production from specific intervals in the wellbore can be ascertained, which might influence completion strategies. For instance, approximately 23% of the produced gas from well 4 appears to originate from a single, contiguous 200 ft measured depth section of the 2600 ft lateral ("A" in Fig. 2), and approximately 50% of the gas is generated from 600 ft or 23% of the horizontal section ("A" + "B" on Fig. 2). Finally, measurement of the intrinsic gas content of the samples distinguishes wells that have been damaged or improperly completed from those that were drilled in a gas-poor section of rock.

Example 3: FIS and XRF for Targeting Sweet Spots:

An example of combining XRF and FIS data to identify and understand sweet spots is illustrated in Figure 4, a horizontal wellbore through a light oil /condensate-bearing section of the Cardium Sandstone, Alberta. This well encountered an unexpected down-faulted section causing the borehole to intersect the overlying shale. The borehole was redirected into the underlying sand near the end of the well. These lithologic relationships are identified by the red (sand) and blue (shale) tick marks on the left side of the figure, which correlate with discrete zones on a silicon vs. aluminum cross plot. The orange bands represent duplicate sections at the top of the sand that have very similar chemical and volatile contents. The red band illustrates dry gas within the shale, possibly related to fracturing in the vicinity of the shale. The gas is clearly drier, and among

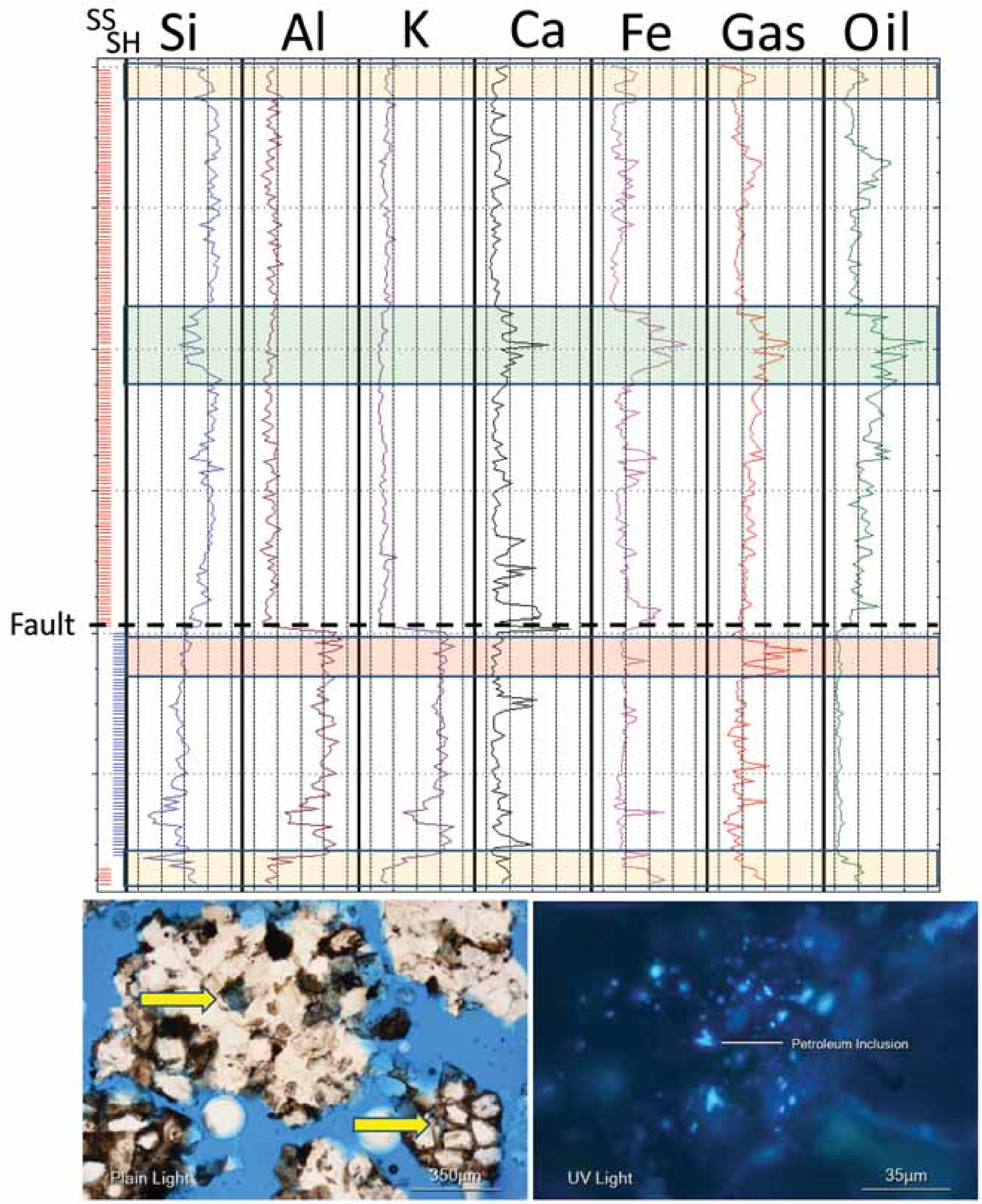

Figure 4. Best production in this horizontal Cardium well (green) correlates with siderite associated porosity and high light-oil-inclusion abundance.

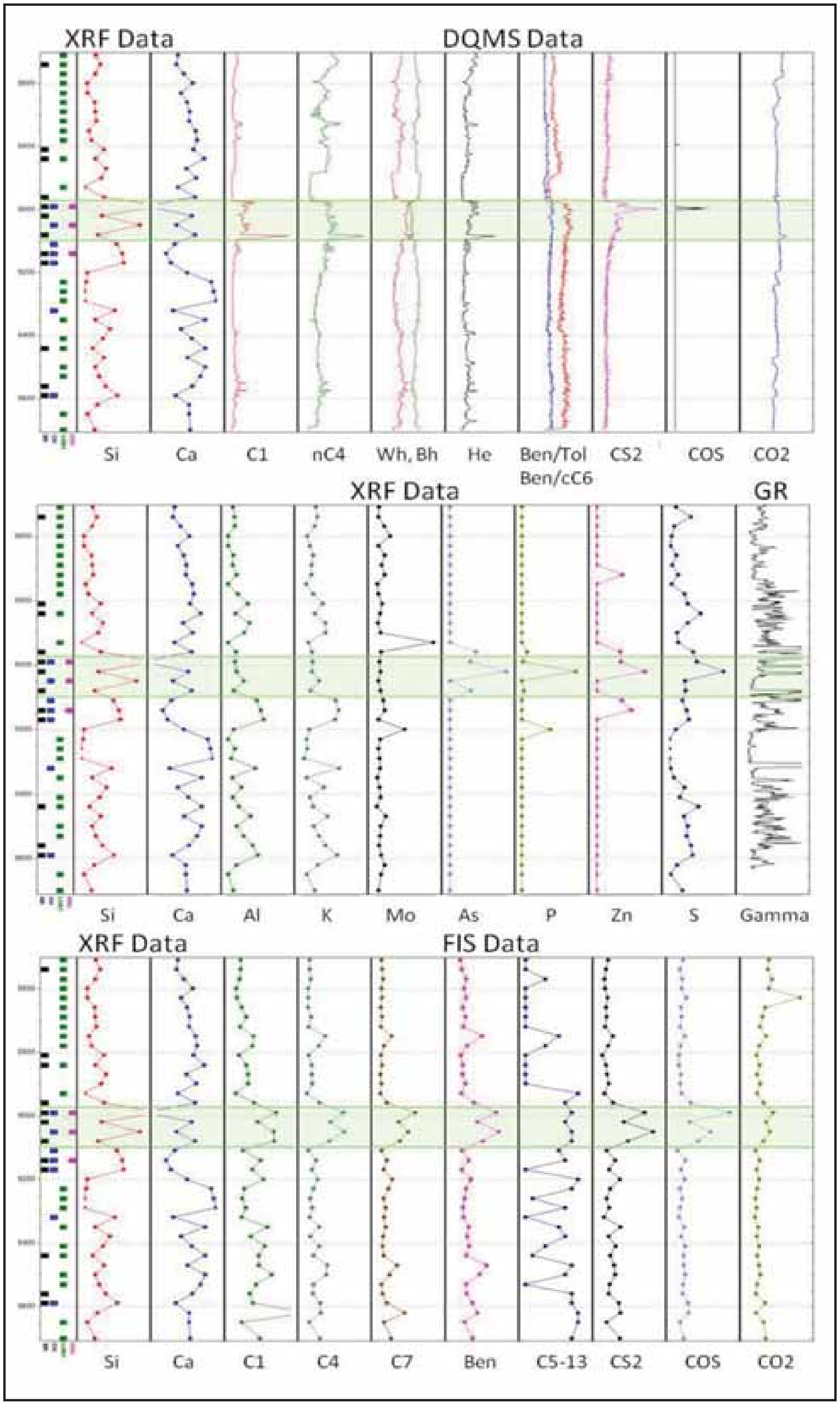

Figure 5. Combined DQMS-XRF-FIS in a liquid-rich fractured cherty carbonate.

other possibilities could indicate introduction of more mature gas from deeper in the system. Of particular interest is the correlation of the highest FIS gas and oil response with decreased silicon and increased calcium and iron shown by the green band. Petrographic work on cuttings indicates that this zone is characterized by siderite-enhanced porosity (yellow arrows lower left image) and higher visual light oil / condensate inclusion abundance (blue fluorescing areas, lower right image). The green zone was tested separately and displayed the highest initial rates in the well. Use of this combined rock and fluid approach on vertical wells can be used to more successfully place laterals.

Example 4: Combining the Techniques:

An example that utilizes both DQMS data and advanced cuttings analysis is presented in Figures 5 and 6. The following discussion concentrates on an interval at approximately 8960 ft to 9110 ft (green interval, Fig. 5). This zone displays a prominent DQMS anomaly characterized by C_1-C_7 species and gas ratios that suggest light oil or condensate (Fig. 5; Panel A). A slightly drier anomaly occurs within a restricted zone and may represent a discrete gassier phase (or gas and oil) as suggested by FIS data described in a subsequent paragraph. Water-saturation indicators (e.g., benzene/toluene and benzene/cyclo-hexane) suggest minor movable water within this section, and the presence of the sulfur species CS_2 and COS suggests that sulfur-bearing volatiles may be produced. Trace amounts of CO_2 are present as well, particularly in the thin drier gas or mixed gas-oil interval.

XRF elemental data (Fig. 5; Panel B) indicate that the main zone of interest is a mixed siliciclastic and carbonate (dolomite and limestone) section with biogenic and terrestrially derived silica (chert and detrital quartz, respectively). Petrographically, the interval is dominated by fractured, cherty carbonate. Aluminum, potassium and iron distribution partly reflect

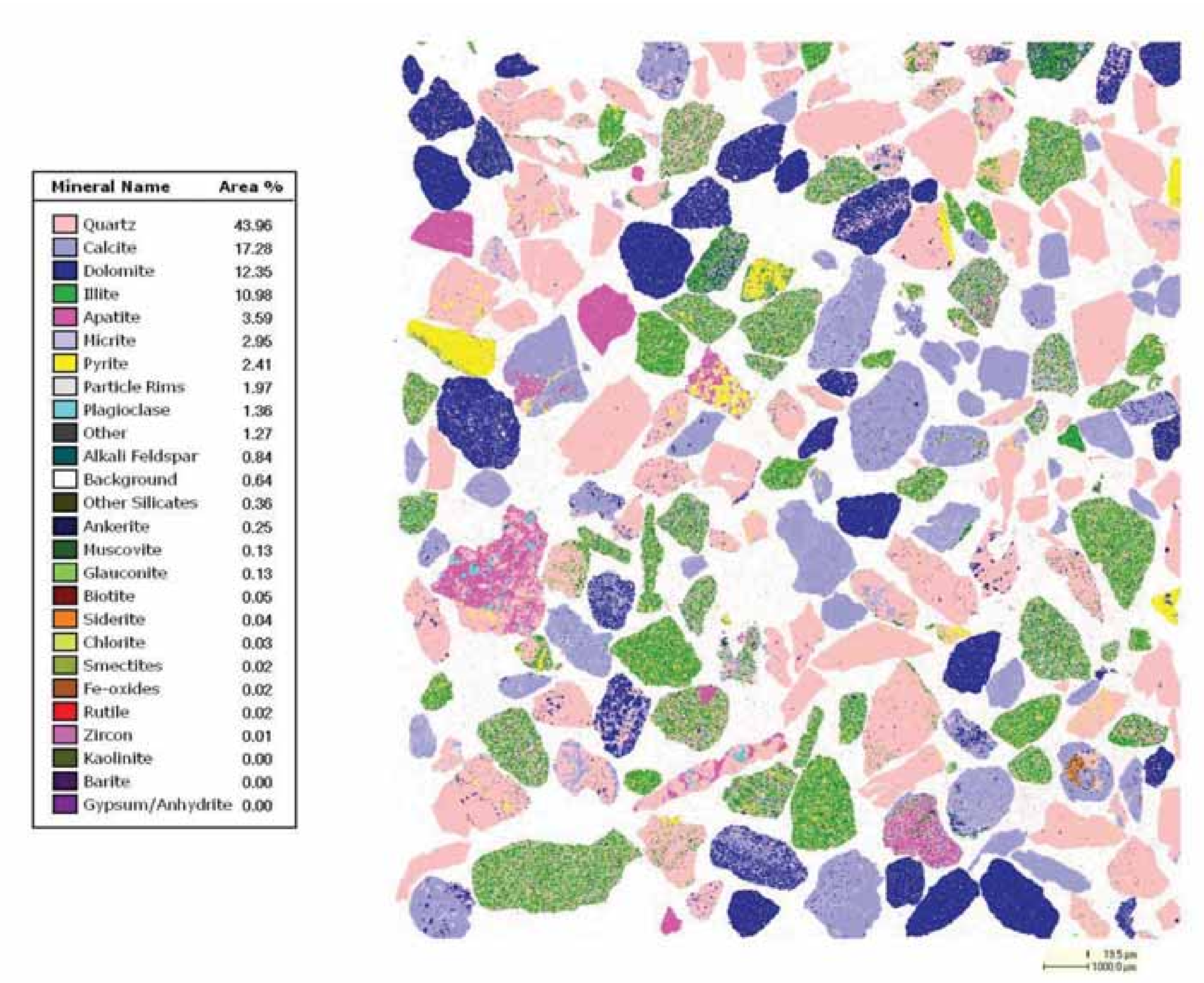

Figure 6. QEMSCAN results from a liquid-rich fractured cherty carbonate (corresponds to 8990 ft in Fig. 5).

clay components, and molybdenum, arsenic, zinc and sulfur may indicate anoxia and the presence of organic matter. The gamma ray correlates fairly well with sulfur, given the differences in sample spacing, consistent with the above interpretation. Petrographic observations indicate the presence of mature oil-prone source rock in some samples. Phosphorus is present, in this case related to the presence of apatite, and may indicate near-shore upwelling environments with high surface productivity. Arsenic is also generally associated with nutrient-rich depositional environments. Mineralogical trends were verified independently via QEMSCAN (see Fig. 6 from 8990 ft). This technique creates a mineral composition map of a petrographic thin section using a rastering scanning-electron-microscope-based energy-dispersive x-ray spectroscopy system and software (Butcher, 2008).

FIS data (Fig. 5; Panel C) indicate species to C_{11}-C_{12} with bulk mass spectra that resemble light oil. Low to middle 40's gravity oil inclusions are abundant in chert, indicating high petroleum saturation. Some gas / condensate is noted as well, suggesting the presence of a dual-phase reservoir, this is consistent with the DQMS observations noted above. FIS C_1 and C_7 relationship imply two discrete charges (oil and dry gas). The FIS data show sulfur species are present, as previously described for mud-gas data, suggesting that some sulfur species (and minor CO_2) may be produced from this zone. These species are interpreted to be of high-temperature origin and probably are related to dry gas that migrated into the structure from deeper in the basin.

In conclusion, the combination of advanced mud gas analysis by DQMS and advanced cuttings analysis via integrated FIS, XRF and photography provides valuable and otherwise unobtainable information with broad application to petroleum exploration and development. These data can be used to help understand the key aspects of conventional and unconventional reservoirs that most commonly contribute to successful exploitation and can aid in optimizing wellbores and completions to lower costs and allow for more efficient drilling strategies.

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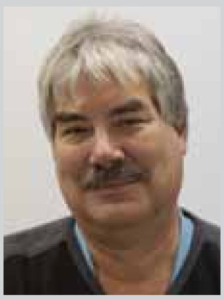
Don Hall

Biographical Sketch

Don received B.S. (1982) and M.S. (1985) degrees in geology from the University of California at Riverside, and a Ph.D. (1989) in geology from Virginia Tech. He joined Amoco Production Research in 1990 as a research scientist where he worked on development and implementation of novel fluid inclusion instrumentation and techniques. He left Amoco in 1997 and co-founded Fluid Inclusion Technologies, Inc. He continues to develop and promote focused applications research and rock/fluid-based analytical programs to help address hydrocarbon exploration and production problems.



Mike Sterner

Biographical Sketch

Mike has a BS in chemistry from the University of Michigan and a Ph.D. in geology from Virginia Tech. After post-doctoral research positions in Germany and at U.C. Berkeley, he joined Pacific Northwest Laboratory where he was involved in thermodynamic modeling of electrolyte solutions. Mike co-founded Fluid Inclusion Technologies, Inc. where he spends much of his time on R&D activities related to instrumentation development.

Ro Shukla

Biographical Sketch

Ro Shukla received his Bachelors in Mechanical Engineering from the University of Mumbai in May, 2005 and his Masters in Mechanical Engineering from the Oklahoma State University in December, 2007. He started working at FIT in March, 2008, where he now serves in the role of the Program Manager for the Dq1000 chemical profiler and as a Senior Technologist.