

ADVANCED MUD GAS AND ROCK-FLUID Analysis Aids Evaluation of North American Unconventional Plays

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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 and other aspects of these complex 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, in part due to variable data quality as well as cost. However, use of more advanced geochemical techniques is enjoying resurgence, in part due to evolution of field instrumentation and more reliable analytical techniques, and is paying dividends for those companies that elect to implement them in routine evaluation of unconventional plays. Of these, the complementary combination of advanced mud gas analysis in the field using gas-chromatography (GC), mass spectrometry (MS) or GC coupled with MS, and comprehensive cuttings analysis for trapped fluids and organic and inorganic makeup in the lab is the most promising. 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.

ADVANCED MUD GAS ANALYSIS:

Recent developments in application of membrane-GC, GCMS and direct

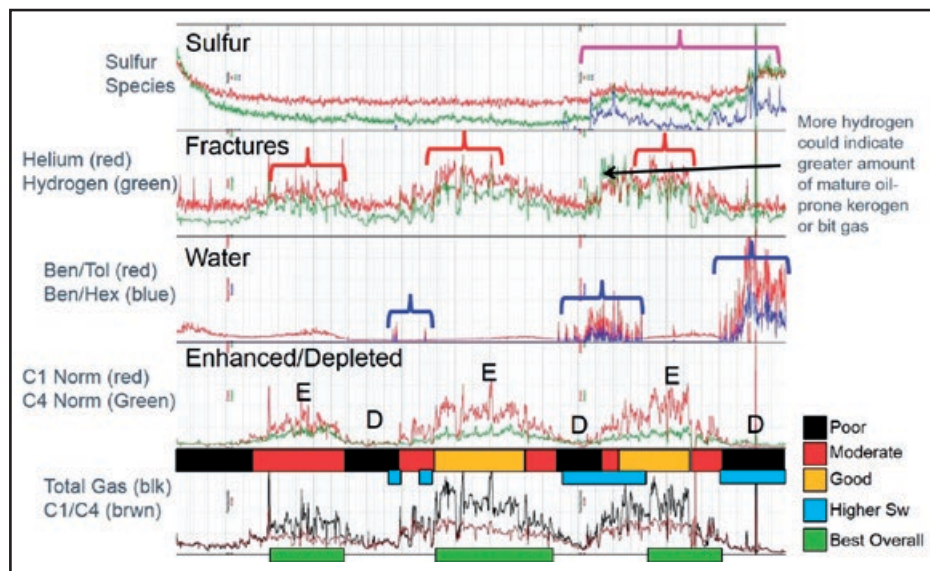


Figure 1: Direct quadrupole mass spectrometry of organic and inorganic volatile species for completion considerations.

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 light years ahead of 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, atmospherics and sulphur-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. The instrument is uniquely suited for organic-base mud systems, which typically hamper data analysis from other devices, and works in low-pressure reservoirs where conventional gear is ineffective. Within unconventional plays DQMS has been used to distinguish among producible hydrocarbon fluid types, identify lower quality or residual systems, evaluate potential for water production,

assess compartmentalization, and recognize fractures and faults. 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. This specific application has tangibly contributed to lower drilling costs, where utilized.

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 XRF analyzer. A key aspect of the process is that all analyses are conducted on the same 1 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.

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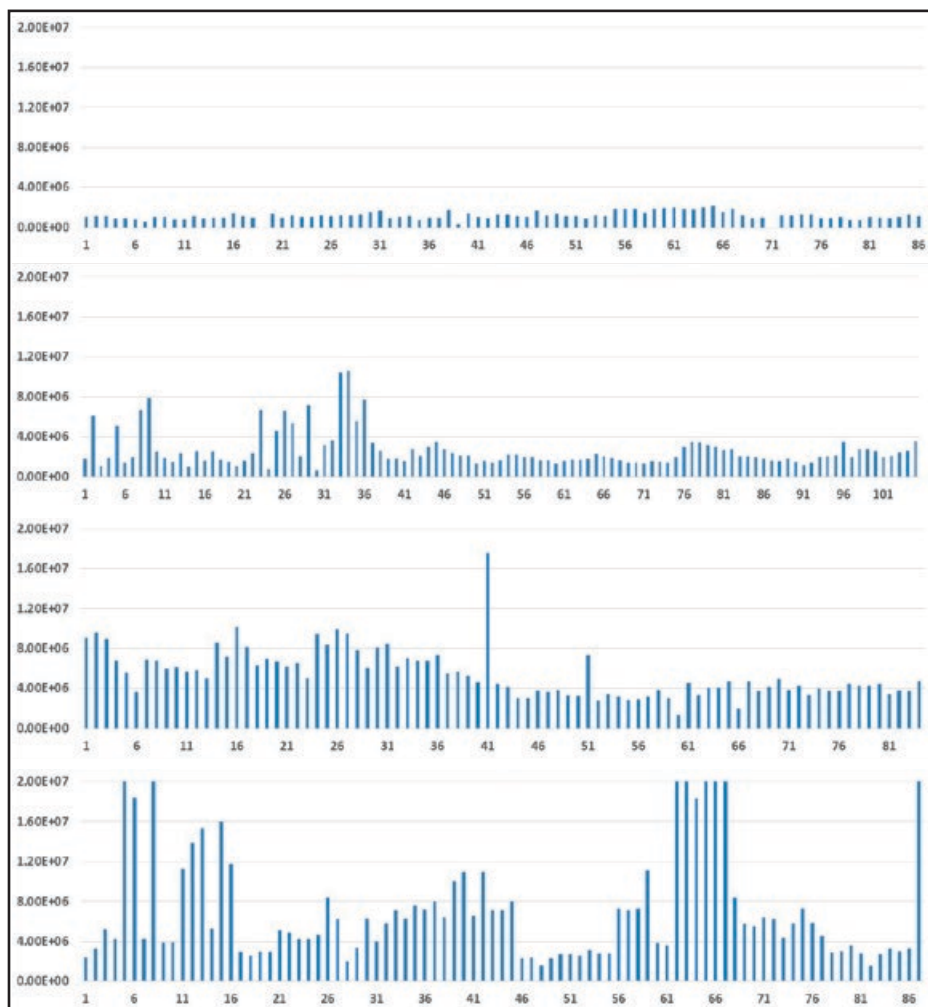


Figure 2: FIS methane response vs sample number, four geographically proximal horizontal wells.

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Together they provide unique insights into controls on hydrocarbon, reservoir and pay distribution, represent an additional tool for well placement, and create an archive 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, 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. XRF data from 30+ major, minor and trace elements in large cuttings sample sets from vertical and horizontal wells can be used 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. Type

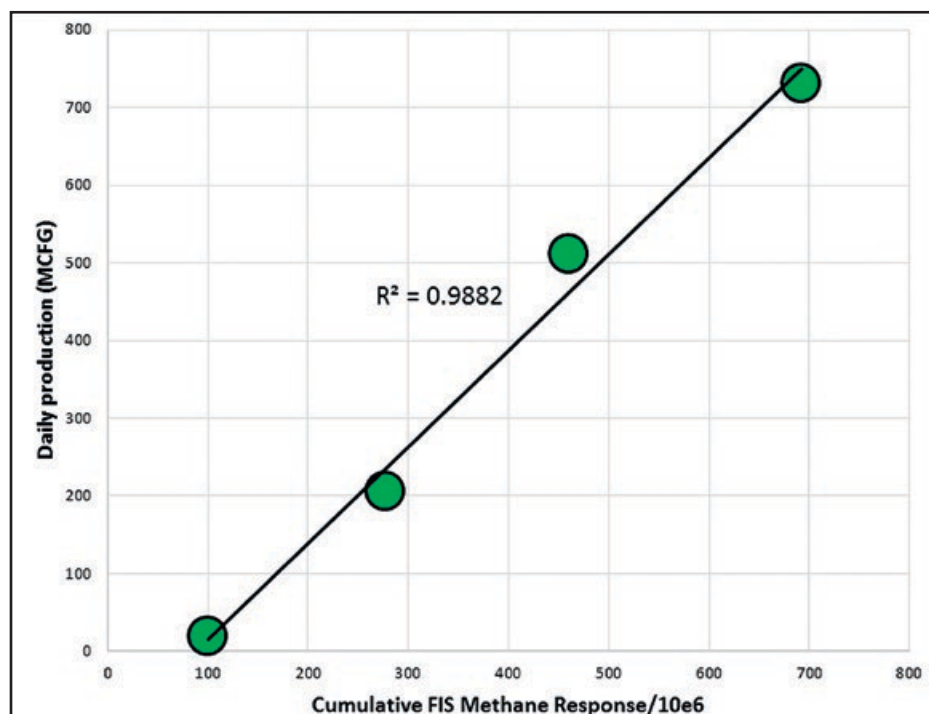


Figure 3: Summed Cuttings Methane Response vs Daily Production; Four Horizontal Wells.

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 system 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 colour can be related to maturity. Archived images are much easier to manage than the samples themselves; they 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 well site.

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 (red brackets, "E" intervals, red and orange bars). The most producible portions of 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

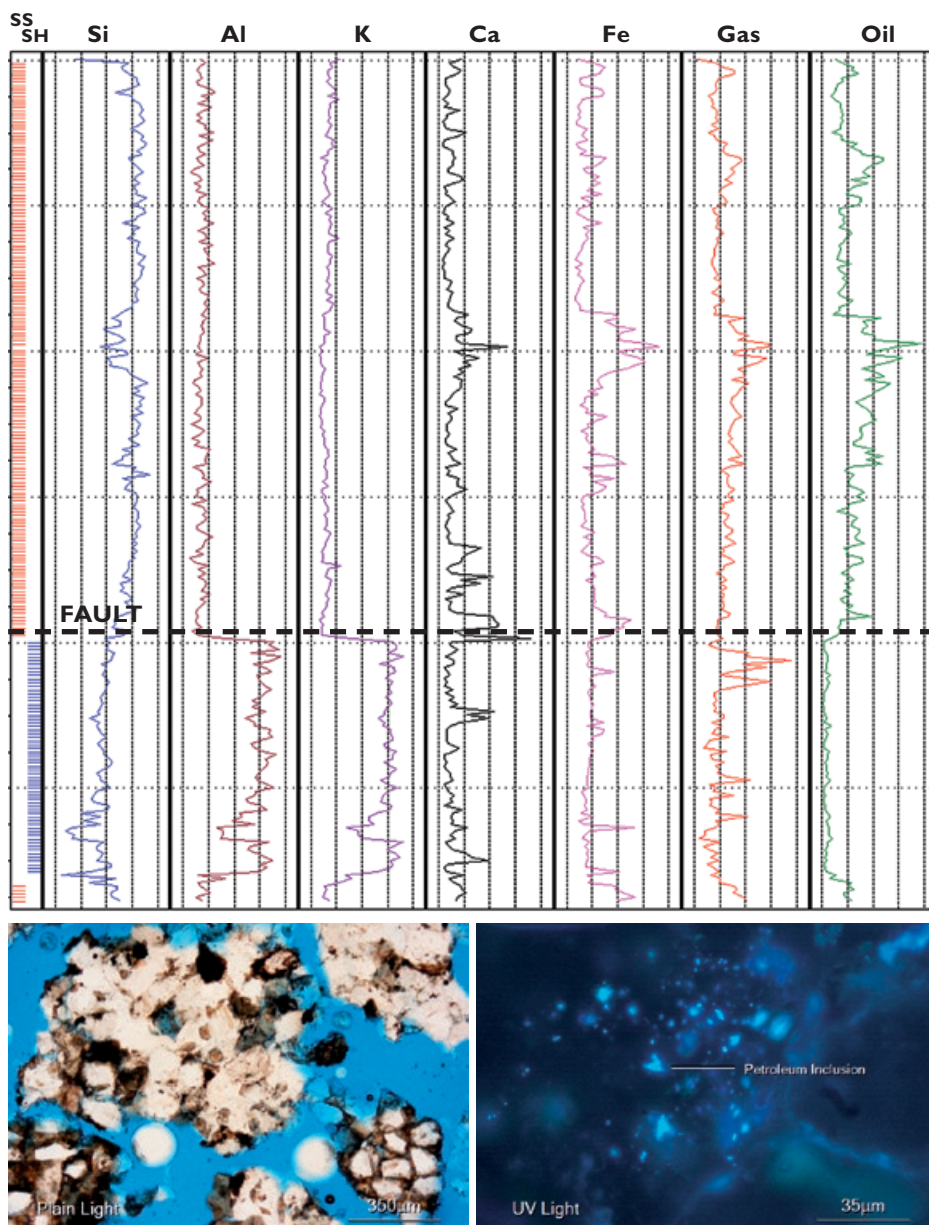


Figure 4: Best production in this horizontal Cardium well (green) correlates with siderite associated porosity, and high light oil inclusion abundance.

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 charge has been dissipated via through-going fractures. The toe of the wellbore contains higher concentrations of sulphur species which may represent an undesirable component of the produced fluid, 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 saturation intervals, because benzene is more soluble in water than both toluene and hexane. Considering all of these data allows one to evaluate the most prospective portions of the lateral based on gas composition, gas quality, deliverability and potential for water production. These 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 are minimal.

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 four horizontal wells within a geographically restricted region are shown as a function of sample number. Data suggest the wells are diverse, both in terms of average response as well as variability through the lateral. Figure 3 illustrates the summed 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 predicted from this calibration set. Furthermore, contributions to the total production from specific portions of 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, and approximately 50% of the gas is generated from 600 ft. or 23% of the horizontal section. Finally, measurement of the intrinsic gas content of the samples distinguishes between wells that have been damaged or improperly completed from those that were drilled in a gas-poor section of rock.

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 trajectory to intersect the overlying shale. The borehole was redirected into the underlying sand near the end of the well. These lithological relationships are identified by the red (sand) and blue (shale) tick marks on the left hand 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, and have substantially similar chemical and volatile response. The red band illustrates dry gas within the shale, possibly related to fracturing in the vicinity of the shale and 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

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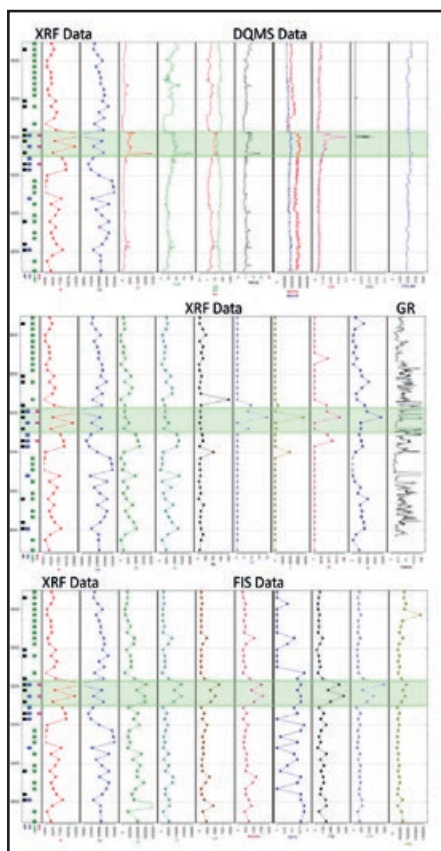


Figure 5: Combined DQMS-XRF-FIS in a liquid rich fractured cherty carbonate play.

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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.

PUTTING IT ALL TOGETHER:

An example that utilizes both DQMS data and advanced cuttings analysis is presented in Figures 5-6. The following discussion concentrates on an interval at approximately 8960-9110 ft. 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 trace movable water within this section, and presence of the sulphur species CS_2 and COS suggests that sulphur bearing volatiles may be produced. Trace CO_2 is present as well, particularly in the thin drier gas or mixed gas-oil interval.

XRF elemental data and element ratios (Fig. 5; Panel B) indicate that the main zone of interest is a mixed siliciclastic and carbonate (dolomite and limestone) section with both biogenic and terrestrially derived silica (chert and detrital quartz, respectively). Petrographically, the interval is dominated by fractured, cherty carbonate. Aluminum, potassium and iron distribution in part reflect clay components, and the species molybdenum, arsenic, zinc and sulphur are potentially indicative of anoxia and the presence of organic matter. The gamma ray correlates fairly well with sulphur, 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 is potentially indicative of 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. This technique creates a mineral composition map of a petrographic thin section using a rastering SEM based EDS-XRF system and software (Fig. 6).

gas-condensate is noted as well, suggesting the possibility of a dual phase reservoir and consistent with DQMS observations above. FIS C_1 and C_7 relationship imply two discrete charges (oil and drier gas). Sulphur species are present in FIS data, as previously described for mud gas data, suggesting that some sulphur species (and minor CO_2) may be produced from this zone. These species are interpreted to be of high temperature origin, and related to dry gas interpreted to have migrated into the structure from deeper in the basin.

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. 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 campaigns.

FIS data (Fig. 5; Panel C) indicate species to C_{11} - C_{12} with bulk mass spectra that resemble light oil. Upper moderate gravity light oil inclusions are abundant in chert, indicating high petroleum saturation. Some

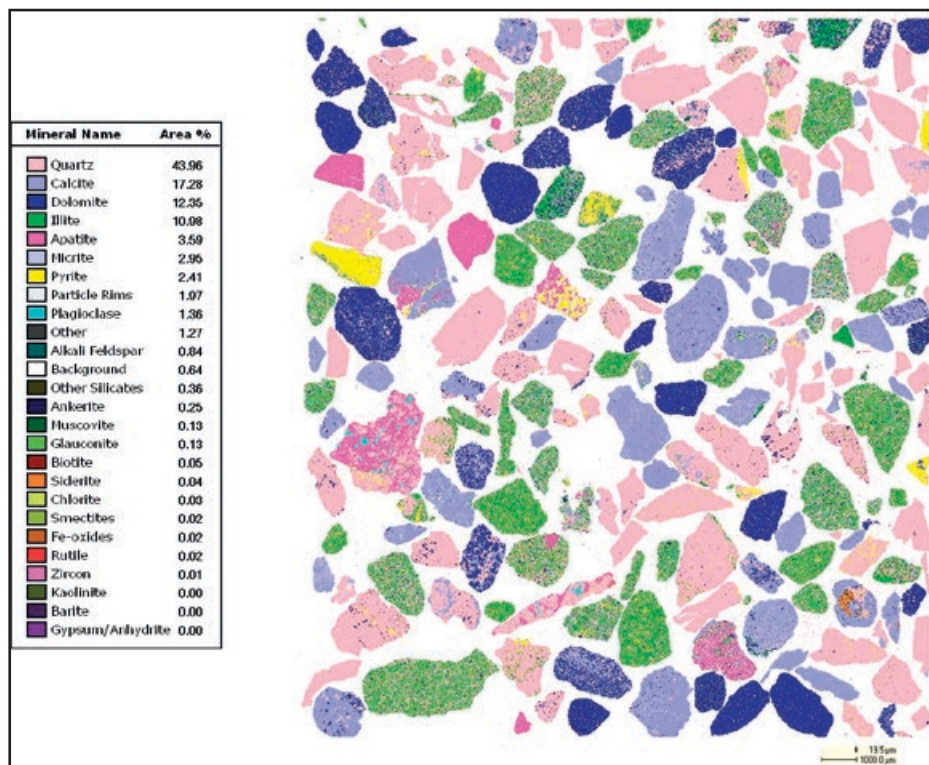


Figure 6: QEMSCAN results from a liquid rich fractured cherty carbonate play.