Characterizing heterogeneities in a clastic reservoir using joint/simultaneous PP/PS inversion, 4D timelapse, Multi Attribute Analysis, and PSDM.

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SUMMARY

In the relatively mature Western Canadian Sedimentary Basin, the primary objective of the geophysics discipline is transitioning from the traditional interpretation of reservoir morphology to include reservoir characterization through the determination of rock and fluid properties. Increasing competition, eroding rates of return, and a decreased tolerance for risk have driven operators to strive to gain as much robust information from their data as possible.

Between 2011 and 2015, Laricina Energy, a privately held bitumen extraction company, acquired both PP/PS 3D and 4D timelapse seismic data over its producing areas. Prestack joint/simultaneous PP/PS inversion, combined with multi attribute analysis allowed for the investigation of both the static and dynamic reservoir. An inability to reconcile the PSTM inversion data to the laterally changing geology of the lower reservoir (and therefore velocities determined during PSTM) warranted processing the data to PSDM.

Ongoing results demonstrate that combining geologic data with compelling analysis products from optimally acquired seismic data can be used to gain meaningful insight as to the physical conditions of both the reservoir and its fluids. As this information is obtained through the life cycle of an E&P project, continual integration and utilization will result in decisions having a higher NPV and could result in more favourable economic results.

Key words: inversion, timelapse, siderite, resource, multi attribute analysis

INTRODUCTION

The Grand Rapids formation of the Upper Mannville Group in the Athabasca oilsands region of northwest Alberta, Canada (Figure 1) consists of a series of at least three stacked shoreface sandstones representing an early Cretaceous (Albian) marine regression and consists of multiple thick sandstones containing 54.5 billion barrels of bitumen in place (EUB, 1996). Figure 2 contains a log identifying the three shorefaces. These shoreface units are represented by stacked offshore marine to beach profiles with varying degrees of erosional interference between the deposits (ERCB 2012). The uppermost shoreface, the Grand Rapids A has the largest accumulation of bitumen with 33.2 billion barrels in place (ERCB 2011). This sand occurs at 225 m average depth in the region of study. Much of the bitumen resource is underlain by a thin bottom water leg of varying thickness as well as a top "lean" zone where bitumen saturations are below 50%, locally. Because of the very high viscosity (>1 000 000 cp) and low gravity (≈8° API) of the bitumen and reservoir depth, extraction and production are achieved *"InSitu,"* most commonly through the Steam Assisted Gravity Drainage (SAGD) technique. In this method, two horizontal wells are drilled parallel into the reservoir, usually with a vertical spacing of about 5 m between them. Steam is then injected into the upper well pair (the injector). The steam heats and effectively "melts" the bitumen, significantly reducing its viscosity. The now "liquid" bitumen is then able to flow under gravity and be pumped from the lower well pair (the producer).

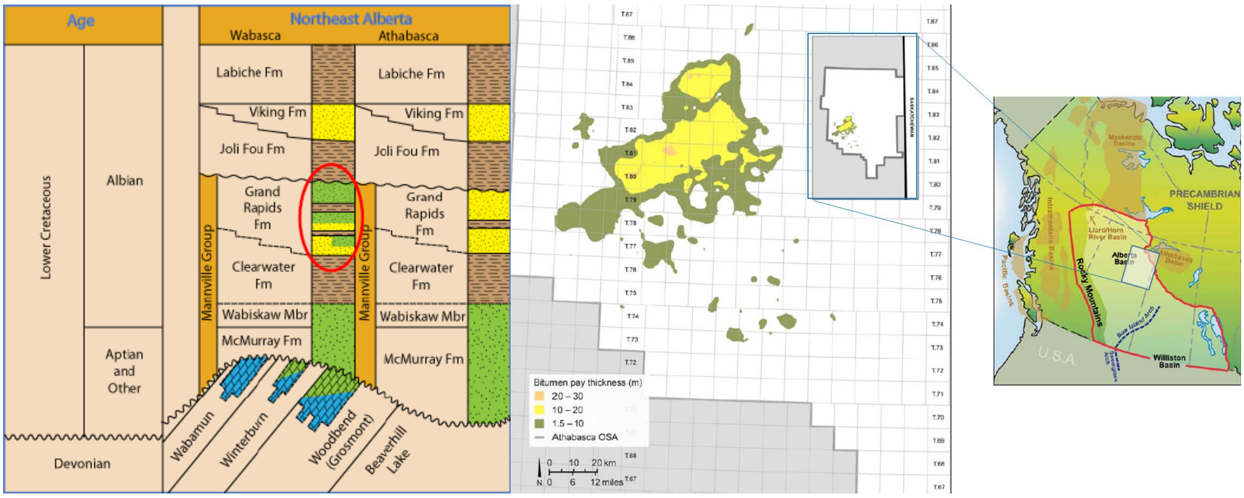


Figure 1: Generalized Upper Manville stratigraphic column and location map for the Grand Rapids formation in the Athabasca oilsands region shown at right.

A prograding regressive shoreface sand, the architecture of the Grand Rapids sandstones is largely laterally and vertically homogenous but with local variations in internal diagenetic history. Typical shoreface features include a cleaning and coarsening upward sequence within the sand body, and downward shoreface structures including carbonaceous swampy facies, low angle planar bedding within the upper beach profile, high angle bedding and cross-bedding of the high energy upper shoreface, swales, hummocks, and low energy, lower shoreface are typically identified. As well, marine ichnofacies are also commonly present.

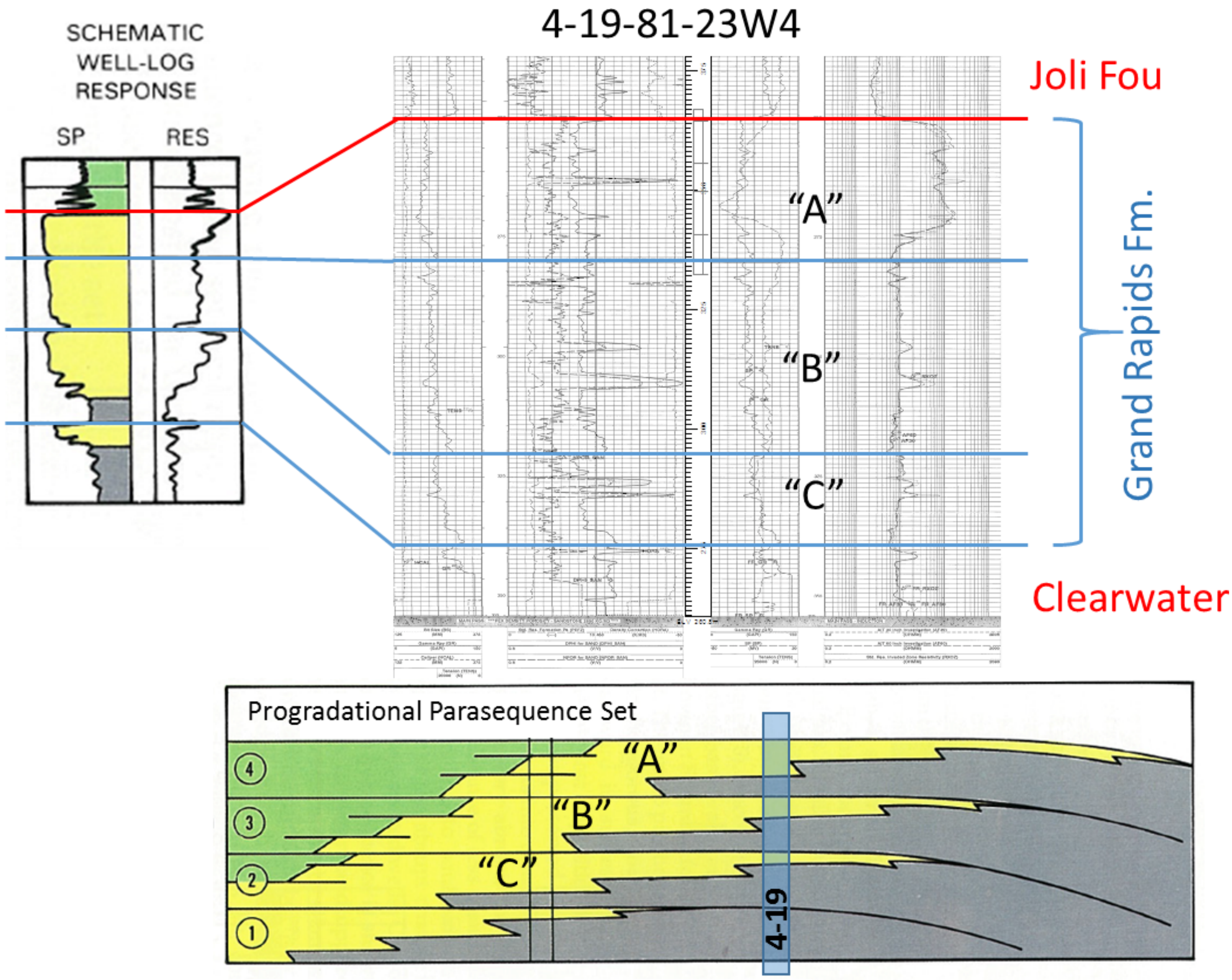


Figure 2: Type log for the upper Grand Rapids reservoir and its depositional setting. Modified from Van Wagoner et al., 1990

The Grand Rapids A is mineralogically immature, with thin section analysis showing grains of mono–crystalline quartz (avg 25%), plagioclase feldspars (avg 15%), chert and polycrystalline quartz (avg 17%), volcanic rock fragments (avg 10%), sedimentary rock fragments (avg 8%) along with a host of minor framework constituents such as alkali feldspars, metamorphic rock fragments, and dolomite grains, etc.. Matrix constituents also vary widely and locally. Clays (most commonly kaolinite) occur within zero to 6% of the sampled sands, averaging possibly 2%.

Within the Grand Rapids, there are three diagenetic pore occluding carbonate lithologies ranging from clean calcite ($CaCO_3$) to siderite ($FeCO_3$). The calcites exist in the form of spherical concretions having a diameter in outcrop ranging from 1-2 m. Where they exist, these concretions tend to occur en masse. In this study area, the concretions are seldom observed in the upper (A) Grand Rapids on logs or seismic, though are common in the middle and lower (B and C) Grand Rapids. The siderites are diagenetic and can be grouped into two general categories. First are thin layers of carbonaceous material occurring in the middle Grand Rapids, and based on log interpretation, are interpreted to be laterally discontinuous when considered against the scale of a SAGD well pad (10's to 100's of meters). They have been related to localized cementation of impurities in the rock, such as shells and pyrite which themselves can be related to local depositional events and changed in sedimentary input. The second has been called a "sideritic mudstone" or "carbonate layer" and is interpreted to have been deposited as a mudstone or shale (transgressive surface or flooding surface), and due to high iron content in the pore fluid, has been completely transformed to a carbonate cement. The log response of calcite concretions can be seen in Figure 2, and both types of siderite are shown in logs in Figure 3.

Origins of diagenetic carbonate minerals can vary and have differing interpretations (Hicks et al.). The purpose here is not to discuss or speculate in detail on the geologic history of these materials in the Grand Rapids. Rather, accepting these layers do exist, the objective of this study is to describe techniques to identify and locate these layers in 3D space. The information would then be used to place the horizontal well pair in areas and zones that are best suited for the SAGD process. These methods can also be used over time in order to quantify their possible effects on reservoir performance.

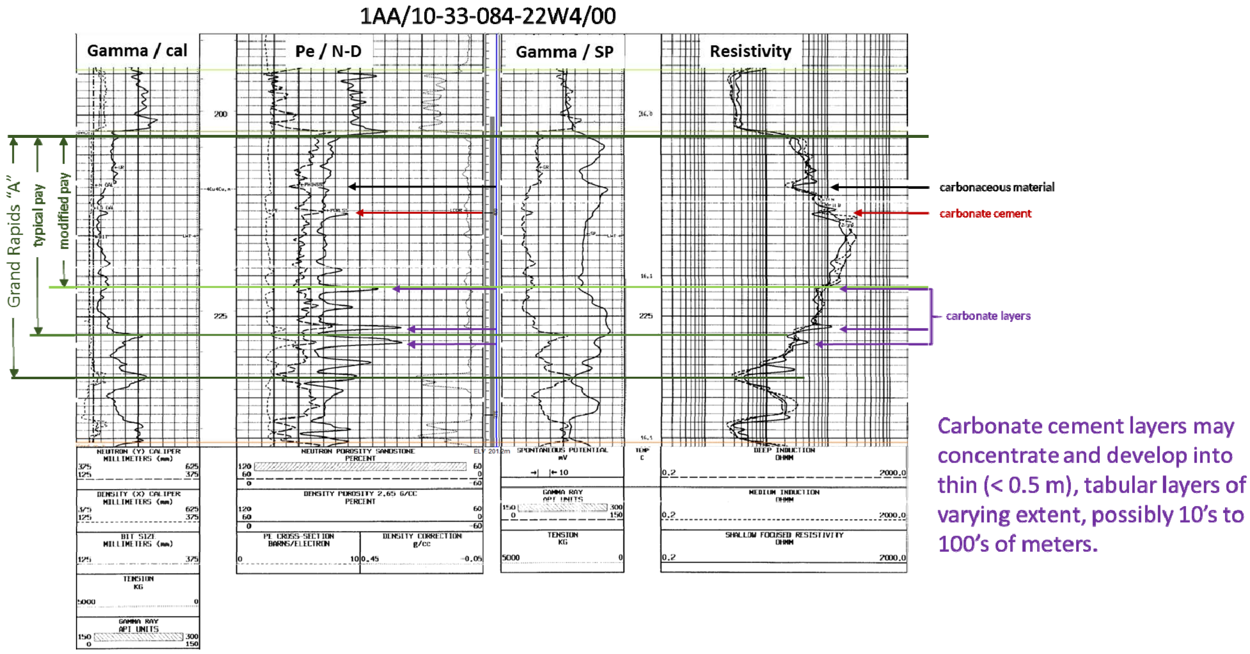
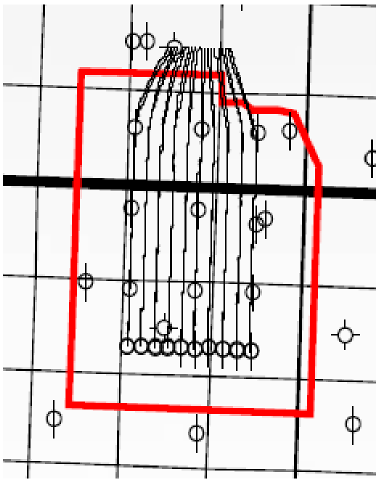


Figure 3: Log suite showing response for the two diagenetic siderite types observed in the Grand Rapids. Carbonaceous material and carbonate cement refer to diagenetic siderite within the Grand Rapids A, while Carbonate layers are also referred to as sideritic mudstones.

Operator experience with "resource" plays has shown in all cases, these reservoirs are not entirely homogeneous, isotropic sand boxes. Although these reservoirs contain significant amounts of exploitable hydrocarbons, subtle geologic heterogeneities must be respected and managed due to the increasing costs of hydrocarbon production (a small SAGD facility and six associated well pairs can cost upwards of eight hundred million Canadian dollars). As such, risk can be minimized, and value maximized by undertaking a detailed geoscience analysis before any exploitation decisions are made. Presented here is how different, and independently obtained geophysical data can be used in conjunction with geologic information in order to obtain information regarding the internal reservoir architecture.

METHOD AND RESULTS

The study area consists of 10 horizontal SAGD well pairs, and encompasses an area of approximately 1.5 km². Figure 4 shows the locations of the horizontal well pairs, 13 vertical delineation wells, and the outline of the seismic surveys (3D and 4D). Acquired after six of the 10 well pairs were drilled, the 3D seismic survey was recorded with source and receiver line spacing of 40 m, and both source and receiver spacing of 20 m. This resulted in good offset and azimuth distribution of data, and a nominal fold of 28 at a depth of 225 m. One year after steaming and production on six of the well pairs (and three months after steaming on the remaining four well pairs), a 4D seismic timelapse monitor using the same parameters was acquired.



In order to determine which geophysical methods and data products should be utilized to characterize the reservoir, attention should be paid to the physical properties of the various lithologies. Figure 5 is a log suite from a vertical well intersecting one of the horizontal well pairs. Identification of the carbonaceous siderite, sideritic mudstone, and calcite (in this location, there is a calcite below the reservoir) are desirable when planning horizontal well placements and reconciling production data and SAGD well performance.

The log response of the calcite (242-246 m) is fairly obvious. The density, compressional, and shear sonic all read extremely high relative to the background sand and shales. The siderites however, are subtler and exist anywhere in the physical continuum between sand/shale, and cemented mud. The sideritic mudstone (222 m) is relatively stiff, having a noticeably higher density, bulk and shear modulus than the clean reservoir, and notably opposite elastic moduli than the shale at the base of the upper Grand Rapids (226 m). Carbonaceous siderite, although having a higher density than the reservoir, is a “mixed bag” of consentient material that results in this unit having variable bulk moduli. This can be seen in the 4 m interval between 214-218 m in the logs of Figure 5.

Figure 4: Location of seismic surveys, horizontal well pairs, and vertical delineation wells. Horizontal wells are 60 m apart, and each black square is 400 m by 400 m.

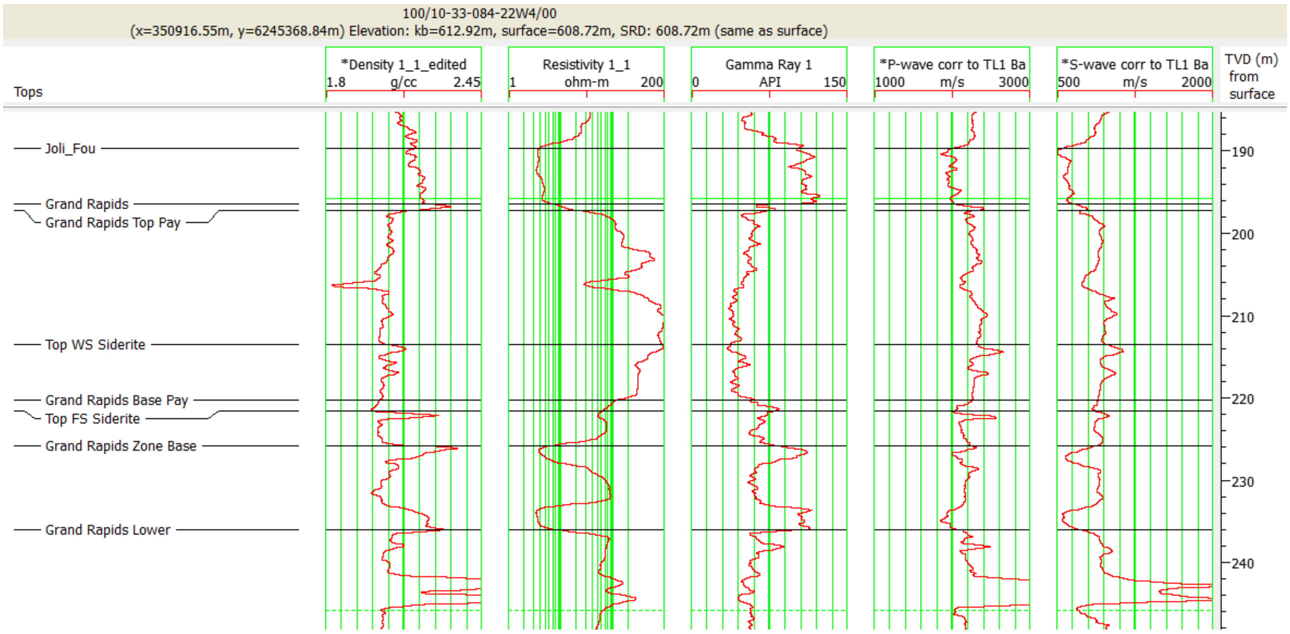


Figure 5: Log suite for the Grand Rapids showing the various physical rock properties for carbonaceous siderites (≈214-218 m), sideritic mudstone (≈222-223 m), and calcite (242-246 m).

Interpretation of the PP seismic data was used to determine both the top and base of the Grand Rapids A. Although conventional PP interpretation was unable to resolve individual siderite layers (presumably due to not enough acoustic contrast from background, and/or being below resolution thickness), calcite deposits can be readily identified on PP seismic as high amplitude, positive impedance events. Conventional PS interpretation provides an indication of regions containing material having a variable shear modulus to the background (possible lithology indicator), however the low frequency of the PS data prevents any detailed interpretation of specific units.

Because prestack inversion removes the seismic wavelet during the process, and has the ability to begin with a first iteration high frequency model based on the well logs (as opposed to the traditional low frequency model simply used to fill in the low frequency components thought to be missing in the wavelet), there is the potential for inversion products to reveal additional detail contained within the PP and PS seismic. Seismic inversion was used to aid in the identification of these units. Both joint PP/PS inversion, as well as joint/simultaneous PP/PS inversion were performed on the 3D baseline before any steaming or production occurred. Both low and high frequency initial models were used, each with variable and constant gamma.

In addition, multi attribute analysis (MAT) was performed using the inversion products and logs as input. In summary, MAT is statistical process by where each seismic trace is transformed into a well log of the desired attribute (porosity, Vshale, Sw, etc.) by the program determining which group of selected inputs (numbering in the hundreds) combine to best transform the seismic trace. Of course, the application of MAT without careful thought and analysis of which attributes the program chooses can result in false positives and misleading results.

Due to the rock physics, the Vp and Vs volumes resulting from inversion are unsuitable for identification of the siderite replacement, and not ideal for the siderite cement (although can be used for shale and calcite). This in turn excluded any MAT result as a tool for siderite identification, with the exception of using MAT to determine density itself.

On its own, the density inversion did aid in the identification of both the siderite cement and replacement. Figure 6 is a cross section from the density volume derived from PP/PS joint/simultaneous inversion with a vertical density log overlain. Although there is a correlation between the log and the top of the reservoir (the seismic depth converted top of reservoir surface is turned on, note the effect of removal of the wavelet in the inversion process at the top of the reservoir), the laterally varying velocities resulting from the variable siderites, calcites and shales prevent the generation of a robust well based velocity model for the time to depth conversion of the inversion products. As such, the events on the density log are offset in depth to the events on the inversion (in Figure 5, the sideritic mudstone and calcite on the inversion are imaged too shallow).

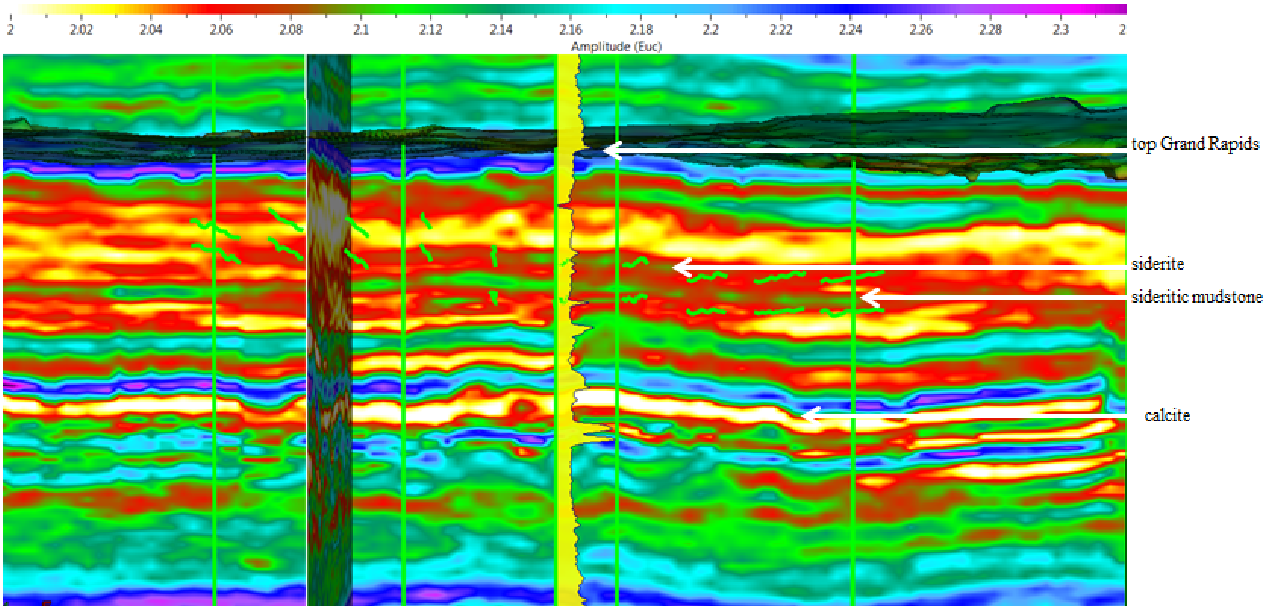


Figure 6: Cross section of density volume from joint/simultaneous PP/PS inversion. Although high density layers within the Grand Rapids are being identified through the inversion process, laterally varying velocities prove problematic for well derived time to depth velocity models. Amplitude units are kg/m^3. Overlain the inversion is the density log from Figure 4.

Independent of the baseline generated inversion products is the information from the timelapse seismic. Primarily used to monitor changes in the reservoir due to fluid and stress changes due to operations and production (i.e. steam chamber development), the timelapse data can also be used to determine the physical effect various lithologies has on production. Figure 7 shows a crossline of the PP baseline, and the same PP crossline of the timelapse. Shown in the time domain, the timelapse section has the same density log overlain as in Figures 5 and 6. The drastic decrease in the compressional impedance shown on the timelapase can only be caused by a noncondensable gas, as thermal models dictate steam would have condensed proximal to the four well pairs that were operational prior to, and during the acquisition of the timelapse. The sudden, drastic, and well defined linear acoustic (positive to negative zero phase is a blue trough) boundary observed on the timelapse data suggests a vertical baffle preventing the free gas migrating upwards. The correlation of the carbonaceous siderite on the density log and the impedance boundary suggests at this time in the operation of the wells, the carbonaceous siderite was a steam baffle. In addition, the timelapse data also supports the operational conclusion that in the three eastern most well pairs, the injectors and producers were drilled such that they were separated by the laterally extensive siderite mudstone, thereby preventing proper communication between injector and producer in these three well pairs.

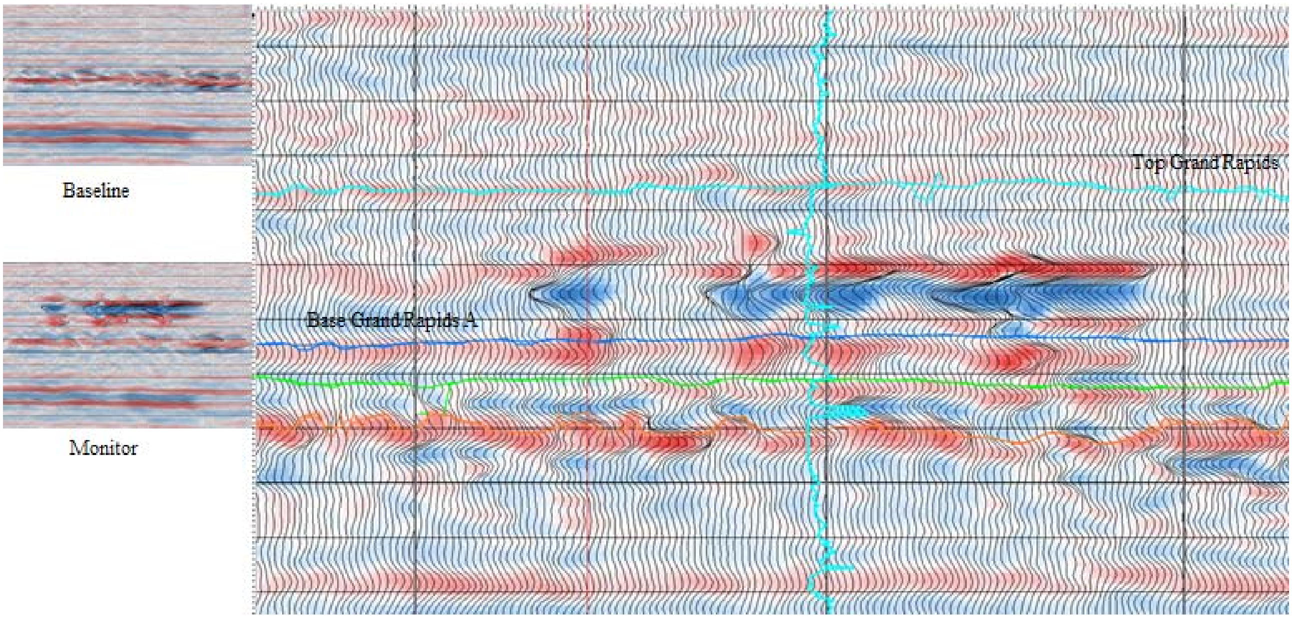


Figure 7: Comparative baseline and timelapse index sections (left) showing the drastic change in impedance between baseline and monitor. In time, the correlation between the locations of the siderites could be causal with the response of the timelapse. The density log from the well in Figure 5 is overlain.

Considerable time was spent developing surface time velocity models using the wells and seismic to generate a velocity model that would reconcile seismic events to logs in the depth domain. Although the models produced a very good result at the top of the Grand Rapids and down through to the base of the Grand Rapids A, this is only because the lithologies are laterally constant. Once the siderites, calcites and basal shales come into play, the three dimensional velocity variations become too severe for any well based velocity model to cope. As such, automated data driven processing in depth was undertaken on the baseline in an attempt to position the energy in its proper spot in the depth domain during processing, thereby not having to rely on time to depth conversion. Currently, methods are being developed to allow software to invert this PSDM data, with the objective of reconciling the uncertainty with the current velocity models.

CONCLUSIONS

Seismic data can be utilized to obtain information regarding the lithologic heterogeneity of the reservoir. However, careful attention must be paid to the subtleties of the rock physics before proceeding. Many iterations of Inversion, MAT, and velocity modelling will likely be required before one obtains a robust result. Reservoir characterization with increasing detail using seismic is an interpretive endeavour that as of yet, has few shortcuts. Yet with many algorithms and workflows, the process can seem arduous and at times frustrating. However, as this study shows, identification of units is not only suggested by comprehensive inversion, but their effect on operations and presence is supported by independent timelapse seismic data, which serve as a check on the inversion and MAT process.

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