ULTRASONIC AND LOW FIELD NUCLEAR MAGNETIC RESONANCE STUDY OF LOWER MONTEREY FORMATION – SAN JOAQUIN BASIN

by

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ABSTRACT

The Monterey formation has a wide variety of lithologies (diatomites and diagenetically derived cherts, porcelanite, organic-rich mudstones, phosphatic, and carbonate rocks) representing the effect of tectonic, oceanographic, and climatic events. Although the Monterey formation has been studied extensively, the lithology has not been correlated with saturation and pore size distributions. Despite recent reports of vast amount of recoverable oil (15.42 billion barrels of technically recoverable oil); no significant hydrocarbon discovery had been made to date in the lower section of Monterey Formation. Current exploration practice of the lower Monterey formation sections use models and techniques from conventional siliciclastic reservoirs. In this thesis, I have investigated the difference between biogenic and detrital silica as well as effects of additional influx of clay and carbonate material in the biogenic lithology.

My work involved a combination of laboratory and well log analysis. The laboratory measurements of seismic velocities and NMR show the effects of mineralogy on ultrasonic velocities and pore size distributions. For example, rocks with considerable amount of carbonate content have higher compressional wave velocity than the silicate rocks. NMR pore size distributions show that small pore sizes in the biogenic quartz phase rocks make up a considerable amount of the porosity. These differences also correlate well with higher (above 0.35) oil/water ratios. Well log analysis reveal that detrital clay content can be identified by high Thorium content from spectral gamma ray log. This increase in clay content can mask reservoir response since it leads to an increase in neutron porosity (NPHI) and lower resistivity values in well logs.
# TABLE OF CONTENTS

ABSTRACT ................................................................................................................................. iii

LIST OF FIGURES .................................................................................................................. vi

LIST OF TABLES ..................................................................................................................... xvii

ACKNOWLEDGEMENTS ........................................................................................................... xix

DEDICATION .............................................................................................................................. xx

1. INTRODUCTION .................................................................................................................. 1
   1.1 Problem Statement ............................................................................................................. 4
   1.2 Objectives .......................................................................................................................... 6
   1.3 Significance of Present Work ............................................................................................ 7

2. GEOLOGICAL BACKGROUND ............................................................................................. 8
   2.1 Geology ............................................................................................................................. 8
   2.2 Tectonic Overprint ............................................................................................................ 12

3. LITERATURE REVIEW ......................................................................................................... 14
   3.1 Silica Diagenesis .............................................................................................................. 14
   3.2 Smectite to Illite Transformation ..................................................................................... 19
   3.3 Organic Matter .................................................................................................................. 22
   3.4 Log Analysis .................................................................................................................... 25
      3.4.1 Standard Logs ............................................................................................................. 25
      3.4.2 Specialized logs ......................................................................................................... 25
      3.4.3 Image Logs ............................................................................................................... 25
   3.5 NMR Measurements ........................................................................................................ 26

4. METHODS AND MATERIALS ............................................................................................. 28
   4.1 Materials ......................................................................................................................... 29
      4.1.1 Core Inventory .......................................................................................................... 29
      4.1.2 Log Inventory ......................................................................................................... 34
   4.2 Experimental Procedure ................................................................................................. 34
      4.2.1 Ultrasonic Measurements ....................................................................................... 34
      4.2.2 NMR Measurements .............................................................................................. 38
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2.3 Log Analysis and core to log comparison</td>
<td>41</td>
</tr>
<tr>
<td>5. RESULTS</td>
<td>43</td>
</tr>
<tr>
<td>5.1 Benchtop Measurements</td>
<td>43</td>
</tr>
<tr>
<td>5.2 Pressure Measurements</td>
<td>45</td>
</tr>
<tr>
<td>5.3 NMR Measurements</td>
<td>52</td>
</tr>
<tr>
<td>5.3.1 NMR Signals</td>
<td>52</td>
</tr>
<tr>
<td>5.3.2 NMR Porosity Calculations and Comparison</td>
<td>55</td>
</tr>
<tr>
<td>6. DISCUSSION</td>
<td>57</td>
</tr>
<tr>
<td>6.1 Ultrasonic Measurements</td>
<td>57</td>
</tr>
<tr>
<td>6.2 Pressurized Ultrasonic Measurements</td>
<td>74</td>
</tr>
<tr>
<td>6.3 NMR Measurements</td>
<td>78</td>
</tr>
<tr>
<td>6.4 NMR and Mercury Injection Relationship</td>
<td>85</td>
</tr>
<tr>
<td>7. CONCLUSIONS AND FUTURE WORK</td>
<td>91</td>
</tr>
<tr>
<td>8. FUTURE WORK</td>
<td>92</td>
</tr>
<tr>
<td>REFERENCES CITED</td>
<td>93</td>
</tr>
<tr>
<td>APPENDIX A. ULTRASONIC MEASUREMENTS</td>
<td>98</td>
</tr>
<tr>
<td>A.1 Core Assembly</td>
<td>98</td>
</tr>
<tr>
<td>A.2 Sample Saturation under Pressure</td>
<td>105</td>
</tr>
<tr>
<td>A.3 Raw Ultrasonic Signals</td>
<td>108</td>
</tr>
<tr>
<td>A.3.1 Benchtop Measurements</td>
<td>108</td>
</tr>
<tr>
<td>A.3.2 Pressurized Measurements</td>
<td>112</td>
</tr>
<tr>
<td>APPENDIX B. NMR Measurements</td>
<td>129</td>
</tr>
<tr>
<td>B.1 Acquisition Parameters</td>
<td>132</td>
</tr>
<tr>
<td>B.2 NMR Porosity calculation</td>
<td>135</td>
</tr>
<tr>
<td>B.3 NMR Background Correction</td>
<td>136</td>
</tr>
<tr>
<td>B.4 NMR and Mercury Injection Comparison</td>
<td>140</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 1.1 Present location of Neogene sedimentary depocenters in California. The figure shows the continuous nature of the depocenter and local tectonic (Behl, 1999)................................. 2

Figure 1.2 Example of different types of fracturing in the Monterey formation at Arroyo Burro beach.............................................................. 3

Figure 2.1 Approximate distribution of Neogene biosiliceous sediments (Ingle, 1981)........ 8

Figure 2.2 Nomenclature variability of Miocene Monterey deposits in California (Behl, 2012). A) Nomenclature used in San Joaquin Basin, B) Nomenclature used in Los Angeles Basin, C) Nomenclature used in Santa Maria Basin....................... 9

Figure 2.3 Deposition in borderland basins, similar to those developed during Miocene time in central and southern California. The San Joaquin basin would be analogous to the “inner basin” (Schwalbach, 1992). ................................. 10

Figure 2.4 San Joaquin Basin Representation. Area being analyzed in this study is highlighted by red rectangle...................................................... 11

Figure 2.5 Sedimentary composition range in the Monterey formation (Isaacs, 1984)......... 12

Figure 2.6 Geologic Map of California displaying some of the main Mesozoic tectonic elements (Ring and Brandom, 1994)........................................ 13

Figure 3.1 Micrograph from scanning electron showing nascent Opal-CT lepispheres growing within a dissolved Opal-A diatom (Behl, 1999)....................... 15

Figure 3.2 Graphical representation of relative timing and temperatures of silica phase changes on diatomites (Behl, 1999). .................................................. 16

Figure 3.3 Changes in physical properties for pure and impure diatomites as they go through diagenesis. Pure diatomite leads to chert while impure diatomite leads to porcelanite (modified from Behl, 2012). ........................................ 17

Figure 3.4 Graphical representation of the different changes in porosity between Opal-A and Opal-CT as proposed by Chaika, 1998 (Chaika and Williams, 2001). ........... 18
Figure 3.5  Figure A represents the expandability of I/S versus temperature (Ramseyer and Boles, 1986) in it Group I is data from oil fields with longer residence times over a particular range during burial. Group II is data from oil fields with shorter residence.

Figure 3.6  Poor to no relationship between biogenic silica and TOC in the Monterey formation (Bohacs et al. 2005).

Figure 3.7  Lack of correlation between TOC and estimated primary production rates of primary organic matter (Bohacs et al. 2005).

Figure 3.8  Differences in relationship between TOC and detritus content. Up until 50% detritus content there is a strong positive relationship, however after 50% detritus content there is an inverse relationship between the two parameters (Bohacs et al. 2005).

Figure 3.9  Bar chart illustrating the range and median value of fracture density measured from cores and outcrop data in the different Monterey rock types (modified from Schwalbach, 1992).

Figure 3.10  Steps taken during NMR processing and analysis. (A) Is the echo train or T2 decay curve, which is in the acquisition time domain. (B) T2 spectrum that is obtained after the inversion process; this data is in the relaxation time domain. (C) T2 spectrum can be divided into clay bound water; capillary bound water, and free movable water. The division comes from different T2 cutoffs (modified from Westphal et al. 2005).

Figure 4.1  Map of California showing Los Angeles Basin, coastal basins, San Joaquin Basin, and outlines the giant fields. Area of study for this research is the San Joaquin Basin and is marked by the purple rectangle in the figure (modified from http://energy.cr.usgs.gov/regional_studies/pacific).

Figure 4.2  Stratigraphic column, spectral and total GR of Wells 1 and 1B showing position of available core data.

Figure 4.3  Core assembly for benchtop measurements. Colored lines represent the different directions in which measurements were taken.
Figure 4.4  Example of core sample assembly for acoustic properties at different angles. ... 37
Figure 4.5  A) Shows a schematic of the sample core assembly (modified from Woodruff, 2012). B) Shows an example of the final core assembly. ............................................ 37
Figure 4.6  Decay of a spin-echo train, which is a function of the amount and distribution of hydrogen present. This type of information can be used to establish pore fluid types and pore size distributions. Points are raw data and the line is a fit (Coates et al. 1999). ........................................................................................................ 40
Figure 4.7  Example of a T2 distribution which is observed through a mathematical process of inversion. With the proper calibration the area under the curve of a T2 distribution is equal to porosity. Additionally because the T2 spectrum is related to pore size distribution, a fixed T2 value will show pore sizes for which fluids below this level will not be able to move and for which above they will be able to move (Coates et al. 1999). ................................................................. 41
Figure 5.1  Compressional wave propagation along four different directions for sample 8935 in Well 1B. Picture of core is included showing the directions. Dashed line marks the start time................................................................. 43
Figure 5.2  Compressional wave propagation along four different directions for sample 7906 in Well 1B. Picture of core is included showing the directions. Dashed lines mark the start of the start time................................................................. 44
Figure 5.3  Example compressional wave propagation at varying pressures for sample 7223.7 for Well 1 at A) 0° and B) 90°. Each color denotes a different pressure step.................................................................................................................. 46
Figure 5.4  Example shear wave propagation at varying pressures for sample 7223.7 for Well 1 at A) 0° and B) 90°. Each color denotes a different pressure step. ............ 47
Figure 5.5  Velocity porosity trends for data obtained from cores samples from Well 1 and 1B. A) Shows an inverse relationship between compressional velocity and porosity; however. B) Shear wave velocity was only obtained from samples from Well 1, an inverse relationship between shear wave velocity and porosity can still be observed. .................................................................................. 49
Figure 5.6  Velocity porosity trends for data obtained from cores samples from Well 1 and 1B. ................................................................. 50

Figure 5.7  Velocity-porosity trends for core samples from Well 1. For each one of the samples the velocities in the 0° and 90° directions are shown. ................. 51

Figure 5.8  Figure shows NMR signals obtained from core samples from Well 1. A) NMR signals for dry samples. B) NMR signals from saturated samples. C) NMR signals from saturated samples after background correction. Red line at 0.06 msec represents the minimum instrument time resolution. ........................ 53

Figure 5.9  Well 1 NMR Signals of Incremental Porosity against time. Area under the curve represents porosity. A background correction has been done for each one of the curves. Red line at 0.06 msec represents the minimum instrument time resolution ....................................................... 54

Figure 5.10 Well 1B NMR Signals of Incremental Porosity against time. Area under the curve represents porosity. A background correction has been done for each one of the curves. Red line at 0.06 msec represents the minimum instrument time resolution ......................................................... 55

Figure 6.1  Map shows oil fields in the San Joaquin Basin. A red star represents the Cymric, McKittrick, and Asphaltto fields which were analyzed by Chaika (1998). The red arrow represents the differences in diagenetic stage from the data obtained by Chaika (1998), starting with Opal-A processing to Opal-CT and later on to quartz. On the same graph the area of this study in highlighted by a dark brown rectangle. This area lies along the Midway-Sunset (MS) field ................................................. 58

Figure 6.2  Compressional Velocity-porosity trends for data obtained from Well 1 and Well 1b along with data collected by Chaika (1998) for Opal-A, Opal-CT, and quartz phase from the San Joaquin Basin. A) Velocity from dry rock samples, B) Velocity after fluid substitution ......................................................... 59
Figure 6.3  Saturated compressional velocity (after fluid substitution) and dry compressional velocity for samples from Well 1, 1B, and that collected by Chaika (1998). Blue line makes line of equality.

Figure 6.4  Shear Velocity-porosity trends for data obtained from Well 1 along with data collected by Chaika (1998) for Opal-A, Opal-CT, and quartz phase rocks of the Monterey from the San Joaquin Basin.

Figure 6.5  A) Map showing the estimated variation in the estimated thickness of the Monterey formation. B) Elevation of Monterey Composite Surface (feet). C) Structure map of the Monterey Composite Surface. Area closed in the rectangle shows current area of study and red line shows section studied by Chaika (1998) (modified from Scheirer, H.A., 2003).

Figure 6.6  Compressional Velocity - Porosity trends for Well 1. Neutron porosity (NPHI) is used for the well log data, whereas helium porosity is used for the laboratory data (Well 1, Well 1b, and Chaika (1998). Notice the separation between the data obtained from the laboratory and that from logs. (Color bar represents depth (ft)).

Figure 6.7  Compressional Velocity - Porosity trends for Well 1. Neutron porosity (NPHI) is used for the well log data as well as velocity data collected for Well 1 and Well 1b data. Helium porosity is used for the data from Chaika (1998). Notice the decrease in separation between the data obtained from the laboratory and that from logs when neutron porosity is used (Color bar represents depth (ft)). Red oval marks the data obtained and analyzed by Chaika (1998).

Figure 6.8  Compressional Velocity - Porosity trends for Well 1 below 6000 ft. Neutron porosity (NPHI) is used for the well log data as well as for Well 1 and Well 1b data. Helium porosity is used for the data from Chaika (1998). (Color bar represents log of resistivity (ohm)). Notice the differences in resistivity between Well 1 (A) and Well 2 (B).
Figure 6.9  Spectral Gamma (track 1), Total Gamma Ray (track 2), and Resistivity (track 3) logs for Wells 1, 1B, and 2. Zones highlighted by the red rectangles are high thorium zones (purple color section on spectral gamma ray track).

Figure 6.10  Compressional Velocity - Porosity trends for Well 1 (A) and Well 2 (B). NPHI is used for log and lab data.). (Color bar: thorium content in ppm). Labels point is oil/water ratios obtained from Dean Stark experiment.

Figure 6.11  Thorium and potassium crossplots for well 1 (A) and well 2 (B). Color scale is log of deep resistivity in ohm-m from log data. Graph shows a decrease in resistivity with an increase in thorium and potassium content.

Figure 6.12  Compressional velocity - porosity trends for Well 2. NPHI is used for the well log data as well as for lab data. Helium porosity is used for data from Chaika (1998). (Color bar: clay content from elemental spectroscopy log (ECS) in decimal percent). Labels for each data point are oil/water ratios from Dean Stark experiment.

Figure 6.13  Compressional velocity - porosity trends for Well 2. NPHI is used for the well log data as well as for lab data. Helium porosity is used for data from Chaika (1998). (Color bar: carbonate content from elemental spectroscopy log (ECS) in decimal percent). Labels for each data point are oil/water ratios obtained from Dean Stark experiment. Zero denotes no data available.

Figure 6.14  Compressional Velocity - Porosity trends for Well 1. Neutron porosity (NPHI) is used for the well log data as well as for Well 1 and Well 1b lab data. (Color bar represents quartz and feldspar content from elemental capture spectroscopy log (ECS) in decimal percent). Values for each data point are oil/water ratios obtained from Dean Stark experiment. Zero denotes no data available.

Figure 6.15  Compressional velocity-pressure trends for core samples from the Monterey formation. Opal-A, Opal-CT, and Quartz data was obtained from Chaika (1998). The data for obtained from this experiment is given along with its respective porosity value.
Figure 6.16  Shear velocity-pressure trends for core samples from the Monterey formation. Opal-A, Opal-CT, and Quartz data was obtained from Chaika (1998). The data for obtained from this experiment is given along with its respective porosity value. 

Figure 6.17  Velocity-porosity trends can be used to identify lithologies. Porcelanites lie in porosities higher than 0.2 and carbonate rich samples have higher velocities.

Figure 6.18  Incremental porosity – time distributions obtained from NMR experiment for core samples from Well 1. The core samples presented in this graph have similar shape. Sample 8154.5 has been crossed out as it had a signal to noise ratio lower than 75. Red line at 0.06 msec represents the minimum instrument time resolution. The black dash line presents the average of the two modes for samples 7220.8 and 7228.2. The blue dash line presents the average of the distribution.

Figure 6.19  Incremental porosity – time distributions obtained from NMR experiment for core samples from Well 1. Red line at 0.06 msec represents the minimum instrument time resolution.

Figure 6.20  Incremental porosity – time distributions obtained from NMR experiment for core samples from Well 1B. Red line at 0.06 msec represents the minimum instrument time resolution. Sample 7906 has been crossed out as it had a signal to noise ratio lower than 75. XRD data for this samples show quartz content higher than 55%. 

Figure 6.21  Incremental porosity – time distributions obtained from NMR experiment for core samples from Well 1B. XRD data for these samples shows total clay content higher than 20%. Red line at 0.06 msec represents the minimum instrument time resolution. Black dash line shows similarities between both samples for the first mode. Blue line represents the average time value for the second mode in core 8288.

Figure 6.22  Velocity porosity trends and it relationship to NMR T2 distributions.
Figure 6.23  Comparison of NMR distributions for Berea Sandstone and quartz dominated rocks from the Monterey formation (cores 5360 and 8935). Quartz dominated rocks from the Monterey formation show distributions at lower time, indicating the presence of smaller pore sizes. ................................................................. 85

Figure 6.24  Relationship between mercury-injection pore size distribution and T$_2$ distribution for sample 7751.8 from well 1. The original mercury injection data was translated by using a $\rho_e$ of 6 um/sec. ................................................................. 87

Figure 6.25  Relationship between mercury-injection pore size distribution and T$_2$ distribution for sample 5477.1 from well 1. The original mercury injection data was translated by using a $\rho_e$ of 1 um/sec. ................................................................. 88

Figure 6.26  Relationship between mercury-injection pore size distribution and T$_2$ distribution for sample 7228.2 from well 1. The original mercury injection data was translated by using a $\rho_e$ of 2 um/sec. ................................................................. 88

Figure 6.27  Well log template for well 1B. Track 1 shows spectral gamma ray, track 2 total gamma ray, track 3 resistivity, track 4 oil (green) and gas (red) shows from mud log, and track 5 calculated capillary pressures from CMR log. In all tracks values increase to the right ................................................................. 90

Figure A.1  Silver electrode and wire used for study. ................................................................. 98

Figure A.2  Compressional Velocity was measured at different angles in the core using panametric transducers in order to determine the directions of maximum and minimum velocities................................................................. 99

Figure A.3  Core sample after electrode holes have been drilled surfaces have been made flat for ultrasonic crystals. ................................................................. 99

Figure A.4  Transducers crystals used for measurements and schematic of cuts made on crystal................................................................. 100

Figure A.5  A) Schematic representation of P- and S-wave crystal preparation. Conducting epoxy is used in one of the surfaces to connect an insulated cable to the surface; this is then covered with 5 min epoxy. The final step is
to cover all surfaces except for bottom with nail polish which will act as electrical insulator. B) Example of final prepared ultrasonic crystal.

Figure A.6 Core sample with crystals and electrodes placed on their respective places. Notice that there is not connection in between the crystals as this could cause a shorting. Additionally there is no connection between the silver epoxy use to connect all of the crystals and the resistivity electrodes.

Figure A.7 Rubber gaskets/ end caps are glued to the flat ends of the core. The individual cables are passing through the feed through in the end caps and pins are solder to them on the other end.

Figure A.8 Properties of EP1121 epoxy made by Resinlab. This epoxy was used for the jacket of the core.

Figure A.9 An example of the final core set up.

Figure A.10 Saturation Measurements Set Up.

Figure A.11 Compressional wave propagation along four different directions for sample 5440 in Well 1B. Picture of core is included showing the directions.

Figure A.12 Compressional wave propagation along four different directions for sample 7906 in Well 1B. Picture of core is included showing the directions.

Figure A.13 Compressional wave propagation along four different directions for sample 8539 in Well 1B. Picture of core is included showing the directions.

Figure A.14 Compressional wave propagation along four different directions for sample 8632 in Well 1B. Picture of core is included showing the directions.

Figure A.15 Compressional wave propagation along four different directions for sample 9097 in Well 1B. Picture of core is included showing the directions.

Figure A.16 Compressional wave propagation along four different directions for sample 9193 in Well 1B. Picture of core is included showing the directions.

Figure A.17 Compressional wave propagation along four different directions for sample 9447.5 in Well 1B. Picture of core is included showing the directions.

Figure A.18 Compressional wave propagation in Sample 7223.7 along P0 direction for different pressures steps. Colors show different pressure steps.
Figure A.19 Compressional wave propagation in Sample 7223.7 along P90 direction for different pressures steps. Colors show different pressure steps. ................................ 113
Figure A.20 Shear wave propagation in Sample 7223.7 along S0 direction for different pressures steps. Colors show different pressure steps. ............................................ 114
Figure A.21 Shear wave propagation in Sample 7223.7 along S90 direction for different pressures steps. Colors show different pressure steps. ............................................ 114
Figure A.22 Compressional wave propagation in Sample 7228.2 along P0 direction for different pressures steps. Colors show different pressure steps. ............................................ 116
Figure A.23 Compressional wave propagation in Sample 7228.2 along P90 direction for different pressures steps. Colors show different pressure steps. ............................................ 116
Figure A.24 Shear wave propagation in Sample 7228.2 along S0 direction for different pressures steps. Colors show different pressure steps. ............................................ 117
Figure A.25 Shear wave propagation in Sample 7228.2 along S90 direction for different pressures steps. Colors show different pressure steps. ............................................ 117
Figure A.26 Compressional wave propagation in Sample 7626.3 along P0 direction for different pressures steps. Colors show different pressure steps. ............................................ 119
Figure A.27 Compressional wave propagation in Sample 7626.3 along P90 direction for different pressures steps. Colors show different pressure steps. ............................................ 119
Figure A.28 Shear wave propagation in Sample 7626.3 along S0 direction for different pressures steps. Colors show different pressure steps. ............................................ 120
Figure A.29 Shear wave propagation in Sample 7626.3 along S90 direction for different pressures steps. Colors show different pressure steps. ............................................ 120
Figure A.30 Compressional wave propagation in Sample 7750.7 along P0 direction for different pressures steps. Colors show different pressure steps. ............................................ 122
Figure A.31 Shear wave propagation in Sample 7750.7 along S0 direction for different pressures steps. Colors show different pressure steps. ............................................ 122
Figure A.32 Shear wave propagation in Sample 7750.7 along S90 direction for different pressures steps. Colors show different pressure steps. ............................................ 123
Figure A.33  Compressional wave propagation in Sample 7751.8 along P0 direction for different pressures steps. Colors show different pressure steps. .................. 125

Figure A.34  Compressional wave propagation in Sample 7751.8 along P90 direction for different pressures steps. Colors show different pressure steps. .................. 125

Figure A.35  Shear wave propagation in Sample 7751.8 along S0 direction for different pressures steps. Colors show different pressure steps. ................................ 126

Figure A.36  Shear wave propagation in Sample 7751.8 along S90 direction for different pressures steps. Colors show different pressure steps. ................................ 126

Figure A.37  Compressional wave propagation in Sample 8154.5 along P0 direction for different pressures steps. Colors show different pressure steps. ...................... 128
LIST OF TABLES

Table 4.1  Conventional Core X-Ray Diffraction data available for Well 1. NA represents not available data. ........................................................................................................ 29

Table 4.2  Rotary Sidewall Core X-Ray Diffraction Data Available for Well 1B. .................. 30

Table 4.3  Porosity, permeability, and saturation data available for Well 1. F/ implies a visible fracture on the core sample. .......................................................................................... 30

Table 4.4  Porosity, permeability, and saturation data available for Well 1B. F/ represents visible fractures in the core sample. ................................................................. 31

Table 4.5  Summary of the samples and type of experiments performed for the study for Well 1........................................................................................................................ 31

Table 4.6  Summary of the samples and type of experiments performed for the study for Well 1........................................................................................................................ 32

Table 4.7  Summary of log data available for the three different wells used in this study. . 34

Table 5.1  Summary of compressional velocities obtained for core samples from Well 1B. Vp1 was measured parallel and Vp2 perpendicular to any aligned textures. The velocities were obtained at benchtop conditions...................... 45

Table 5.2  Summary of Vs0, Vp90, Vs0, Vs90 velocities obtained for core samples from Well 1. The velocities were obtained at a confining pressure of 1000 psi.......... 48

Table 5.3  Table shows the calculated porosity values from NMR T2 distributions for Well 1. Comparison against NMR porosity shows some agreement with the porosity obtained from Corelab (helium). However, porosity values from NMR are lower than the density porosity and neutron porosity values from well logs. ........................................................................................................... 56

Table 5.4  Table shows the calculated porosity values from NMR T2 distributions for Well 1B. Comparison against NMR porosity shows that it is in good agreement with the porosity obtained from Corelab (helium). However, values deviate from those obtain by CMR tool and Density Porosity.................. 56
**Table 6.1**  Effective surface relaxitivity found for cores from well 1 and mercury injection porosity. .............................................................. 89

**Table A.1**  Ultrasonic values obtained for sample 7223.7’ in Well 1. Table shows the values for compressional and shear velocities in two different directions during pressure loading and unloading. ............................................................................ 112

**Table A.2**  Ultrasonic values obtained for sample 7228.2’ in Well 1. Table shows the values for compressional and shear velocities in two different directions during pressure loading and unloading. ......................................................... 115

**Table A.3**  Ultrasonic values obtained for sample 7626.3’ in Well 1. Table shows the values for compressional and shear velocities in two different directions during pressure loading and unloading. ................................................. 118

**Table A.4**  Ultrasonic values obtained for sample 7750.7’ in Well 1. Table shows the values for compressional and shear velocities in two different directions during pressure loading and unloading. ................................................. 121

**Table A.5**  Ultrasonic values obtained for sample 7751.8’ in Well 1. Table shows the values for compressional and shear velocities in two different directions during pressure loading and unloading. ................................................. 124

**Table A.6**  Ultrasonic values obtained for sample 8154.5’ in Well 1. Table shows the values for compressional and shear velocities in two different directions during pressure loading and unloading. Notice the negative values of Poisson’s Ratio; this shows that the data was unreliable for this core. .............. 127
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DEDICATION

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1. INTRODUCTION

Siliceous deposits can be described as fine grained silica-rich sediments and sedimentary rocks, which include chert, siliceous shale, and diatomites. Some of the primary minerals that make up siliceous deposits are amorphous silica (Opal-A), cristoballite (Opal-CT), tridymite, chalcedonic quartz, microquartz, and the various combinations of these phases. The source of silica in these sediments is most commonly opaline biogenic debris, such as radiolarians, silicoflagellates, and diatoms. The tests and frustules of these marine organisms accumulate in great quantities over extensive areas of the sea floor. Siliceous deposits are most common in polar-regions, the equatorial belt, and other areas where cold nutrient rich water upwell, such as offshore California, North Africa, and Peru (Tada and Lijima, 1983). The Monterey formation is one of the world’s most famous siliceous deposits. It has vast amounts of diatomites and diagenetically derived cherts, porcelainite, as well as organic-rich mudstones, phosphatic, and carbonate rocks. The Monterey Formation is a representation of the effects of climatic, tectonic, and oceanographic events that came together to give this formation its unique characteristics.

The Monterey formation is the primary source rock in California (Figure 1.1), it is also the reservoir for many oil fields (Behl, 1999) and has been studied extensively (Blake et al. 1978; Ingle, 1981; Barron, 1986a). Recent reports of recoverable oil (for example, the United States Energy Information Agency, EIA report, 2011) have reignited interest in the Monterey Formation. The EIA (2011) estimates the Monterey/Santos formation as having 15.42 BBO (Billion Barrels of technically recoverable Oil). This is about 4-5 times bigger than the estimates for the Bakken and the Eagle Ford formations (estimated at 3.6 and 3.4 BBO, respectively). Although the Monterey formation does not have continuous areal extent (Figure 1.1) it, does have a great thickness (1,000 to 3,000 ft) with considerable organic richness (average 2 - 5% by weight, locally as high as 23%) (Behl, 1999). Thus, understanding reservoir properties of biogenic silicates coupled with recent studies in shale reservoir developments can give the Monterey formation great reservoir potential and aid in its successful development.
The Monterey formation contains unique reservoir rocks and complexity due to fractures. A majority of the rocks contain a high proportion of biogeneic silica derived from diatoms (Behl, 1999). The diatomaceous rocks are deposited as Opal-A (amorphous silica) that transforms into Opal-CT (cristobalite-tridymite) and quartz with increasing burial depth and temperature. Some of the primary reservoir rocks are porcelanites, cherts, siliceous shales, and dolomites. The strata are thinly-bedded, heterogenous, fractured, and overall difficult to adequately describe and analyze using standard reservoir characterization techniques (Schwalbach et al. 2009). Figure 1.2 shows an example of lithology and fracture variations of the Monterey formation in an outcrop at Arroyo Burro beach in California.
The deeper quartz phase rocks have been speculated to have the potential for commercial hydrocarbon production. However, a major cause for limited exploration success is the lack of a systematic study of, as well as a paucity of data on the physical properties of the Monterey formation lithologies. I have addressed this gap by studying the quartz phase of the Monterey formation. My approach focuses on using laboratory and log data to investigate pore size distributions and porosity-velocity trends. The methods for this investigation include
laboratory nuclear magnetic resonance (NMR) and ultrasonic measurements as well as log data. I have attempted to interpret and understand the logs using lab data in order to better quantify the pore space and examine the controls these factors exert on reservoir performance. One major consideration of this work was to investigate the difference between upper and lower sediments of the Monterey formation.

The thesis is arranged as follows: all background material, such as Introduction, Problem Statement, Objectives, local Geology, and background is presented in Chapter 1-3. Chapter 4 describes the Methods, Samples and Data used in the thesis; Results are presented in Chapter 5 and Discussed in Chapter 6 with Conclusion derived in the thesis in Chapter 7. The appendices contains step by step introduction on core assembly, sample saturation, NMR measurements and corrections.

1.1 Problem Statement

This work is motivated by ongoing discrepancies during reservoir characterization of the Monterey Formation using knowledge gained from conventional sandstone reservoirs. A few of these problems are discussed below:

- Understanding Porosity Development in Biogenic Silicate Reservoirs

A tremendous amount of work has been done to understand porosity and the effect of fluids on siliciclastic detrital rocks, namely conventional sandstone reservoirs. For example, porosity reduction in sands and sandstones by mechanical compaction, grain-boundary dissolution, and grain crushing are well established (Houseknecht, 1984; Wong and Baud, 1999; 2009). Sandstone porosity has been inversely correlated with velocity (Nur et al. 1998); experimental data of Han et al. (1986) have shown that velocity reduction in sandstones can be directly related to the amount of clay minerals present in the rocks. In the presence of water, while the bulk modulus of these clay minerals increases as expected, their shear modulus
decreases. Furthermore, Han et al. (1986) concluded that differences in consolidation among dry sandstones are overwhelmed by the effects of water saturation.

In contrast to sandstones, the Monterey formation, consists primarily of biogenic non-granular siliceous material. Siliciclastic detrital material such as sand is only secondary. In contrast to detrital sandstones, silica diagenesis plays a major role in porosity development in biogenic siliceous reservoirs. Pisciotto (1981) and Keller and Isaacs (1985) analyzed the decrease in porosity in biogenic siliceous sediments in its transformation from Opal-A (65% porosity), to Opal-CT (30% porosity), to quartz (10% porosity). In order to better understand this porosity destruction, more research is needed for each of the different phases of silica diagenesis and on the changes in pore size distributions with silica diagenesis.

Chaika (1998) provided some information on porosity changes with variations on non-silica materials. However, all samples studied by Chaika (1998) had porosities greater than 20%. It is critical to expand our understanding below this porosity range as they will better represent the behavior of rocks from deeper depths in the Monterey formation.

The Monterey formation in the San Joaquin Basin has thicknesses in the range of thousands of feet, a significant amount are rocks in the quartz phase. A systematic investigation of the pore structure and its correlation, if any with velocity would be beneficial to understand and distinguish the velocity-porosity relationship in biogenic quartz formations. Although the quartz phase rocks lie deeper and thus have the potential for new resources, to date no significant hydrocarbon discovery of hydrocarbons has been made. This can be due to the fact that identifying a reservoir or pay zone is a challenge.

- **Velocity-porosity trends in Biogenic Silicate Reservoirs**

Any exploration of the Monterey formation, will require more indirect methods such as seismic waves to determine porosity on a spatial scale. This presents a problem as many of the common assumptions and empirical relations are not necessarily applicable to source-rock reservoirs (shales or mudstones). For example, the mineralogical composition of many source-
rock reservoirs need not be dominated by clays and so the models developed for clay-dominated mudstones are not appropriate. Additionally, the mudstones of source-rock reservoirs are for the most part dominated by biogenic calcite or biogenic quartz (Hart et al. 2013). Most empirical relations, such as the velocity-porosity correlation as function of clay content (Han et al. 1986) were derived for clastic, detrital sandstones. The Monterey formation, with vast amounts of biogenic sediments, will require a different type of analysis and models. Any velocity systematics will also need to address effects of textural anisotropy on seismic and transport properties. While such anisotropy may be incidental in clastic reservoir formations, it is almost essential in mud rock and shale lithologies.

Most of the samples in the Monterey formation contain laminations that have an effect on velocity values. Generally, it has been found that mudstones of source-rock reservoirs can but need not be anisotropic in the lamination scale of millimeters, the scale of core samples. However, they are always anisotropic in the bed scale of centimeters to meters (Hart et al. 2013). It will be important to establish if anisotropy will be a factor in the Monterey formation at each scale, whether it is core or bed scale. Any porosity inversions from seismic and well log data will need to account for velocity anisotropy.

1.2 Objectives

In the present work, I had the following objectives in order to study the pore size distribution and porosity-velocity trends from quartz phase rocks from the Monterey Formation.

1. Distinguish porosity-velocity trends and assess amount of velocity anisotropy in siliceous non-granular rocks.
2. Understand pore size distributions in the quartz phase rocks.
3. Understand the effects of pore types on velocity and moduli.
4. Interpret logs using lab data.
1.3 Significance of Present Work

In the absence of published data on quartz phase rocks from the Monterey formation, assumptions are made that once these rocks have reached the diagenetic stage of quartz, most of the porosity has been lost and they are not be seen as ideal rock types for hydrocarbon storage and production. However, Bohacs et al. (2005) have shown that presence of other minerals such as clays or carbonates can slow these diagenetic changes. The focus of this thesis is to investigate existence of any pore size distribution variations within the quartz phase rocks from the Monterey formation and their relation to mineral compositions and detect any direct implications to reservoir performance.

An understanding of such relations will allow us to better characterize the reservoir and evaluate its economic value. With the continued and increasing demand for oil, the ability to explore different and deeper areas of the Monterey formation would be immensely valuable. Seismic data acquisition and interpretation is a key exploration tool that has the ultimate purpose of determining rock properties such as porosity on a spatial scale. In order for this seismic interpretation to be performed correctly, the velocity-porosity trends and velocity anisotropy understanding developed in the thesis will be critical.

With these concerns in mind we decided to investigate porosity-velocity trends for these siliceous non-granular rocks, understand the effects of pore types on the velocity and moduli. Additionally, since laminations and fractures are a characteristic of the Monterey formation the velocity anisotropy is also taken into account. Finally, we use the knowledge acquired from the laboratory measurements to interpret lab data.
2. GEOLOGICAL BACKGROUND

2.1 Geology

The Monterey Formation was deposited along the North American plate boundary during the transition of the California margin from a convergent to a transform setting (Blake et al. 1978; Barron, 1986a). Between late Oligocene and Miocene subsidence occurred, possibly caused by adjustments in tectonic plates and increased spreading rates for the Pacific plate. The structural changes led to the creation of bathyal depocenters in which Monterey sediments accumulated. During the Miocene, expansion of Antarctic glaciation occurred leading to an increase in the global temperature gradients. The increase in ocean temperature led to an increase in ocean circulation (Figure 2.1) that in turn led to an increase in upwelling. This increased upwelling and ocean circulation led to high amounts of biogenic siliceous sediment being deposited in some coastal areas around the Pacific Ocean (Ingle, 1981).

![Figure 2.1 Approximate distribution of Neogene biosiliceous sediments (Ingle, 1981).](image)

These siliceous Miocene strata rocks have been given different names in different areas in California (Figure 2.2). For example, the same late Miocene sediments are called the Modelo formation in the Los Angeles basin, the Siquoc Formation in the Santa Maria Basin, and the Reef Ridge formation in the San Joaquin Basin. This variation in nomenclature for each basin and for
the fields within the basins result from their different properties and characteristics associated with them. For example, the Elk Hills field in the San Joaquin basin produces from an anticline whereas the North Shafter field is located on a homocline sealed by a facies change from Opal-CT to quartz (Schwalbach et al. 2009). This variation in nomenclature, structure, lithology, and reservoir properties prevents sharing knowledge and best practices between basins and fields.

Figure 2.2 Nomenclature variability of Miocene Monterey deposits in California (Behl, 2012). A) Nomenclature used in San Joaquin Basin, B) Nomenclature used in Los Angeles Basin, C) Nomenclature used in Santa Maria Basin.

These different basins formed as result of the depositional environment of the Monterey formation. Figure 2.3 shows the proposed topography for the environment of deposition of the Monterey formation (Schwalbach et al. 2009). This topography is a result of the complex history of extension, translation, and rotation changes that occur along the California margin as it evolved from subduction to a transform plate margin. Figure 2.3 shows how it would be more likely for coarse grained clastic sediments to be trapped and accumulated in the inner basins and depressions closest to the mainland; the San Joaquin basin which is close to the mainland and bounded by the Sierra Nevada range on the east and the San Andreas fault on the west is an example of this type of inner basin. On the other hand, pelagic and hemipelagic sediments would dominate the outer basins farthest away from the shoreline.
of the Monterey period. The Santa Barbara basin is an example of this type of sediment deposition. One similarity that both types of basins share is that diatomites make up only the upper part of the sediment column while harder siliceous rocks such as porcelanite, porcelaneous shale, cherty shale, and chert make up most of the formation. Older stratigraphic units tend to be generally laterally restricted while younger sediments such as diatomites are continuous over wide geographic areas especially in outer basins.

Additionally, other types of deposits are also found in the Monterey formation. For example, the increased volcanic activity during the transition from subduction to a transform margin setting is marked by inter-bedded volcanic deposits of Miocene age; deep gravity flows formed coarse sand packages such as Stevens sands in the San Joaquin basin (Schwalbach et al. 2009).

![SCHEMATIC MODEL FOR BORDERLAND BASINS](image)

Figure 2.3 Deposition in borderland basins, similar to those developed during Miocene time in central and southern California. The San Joaquin basin would be analogous to the “inner basin” (Schwalbach et al. 2009).

The Monterey formation is an extensive oil-bearing formation that has distinct inner and outer basins (Figure 2.3). For this study, we will concentrate on the inner Monterey basin,
namely the San Joaquin Basin, which holds major oil fields, such as the Midway Sunset, the Elk Hills, and the Buena Vista fields (Figure 2.4). The rocks in this basin are typically thinly-bedded, heterogeneous, and contain micro-fractures. Oil production in the San Joaquin basin comes from cherts and diatomite deposits of the Monterey formation. In this area, the Monterey formation serves as the reservoir and the source rock. The Monterey formation in the San Joaquin basin differs from that of the coastal and offshore basin in that it displays a greater degree of dilution of biogenic components by fine-grained terrigenous lithologies (Graham and Williams, 1985).

One of the sources for the terrigenous content was the San Andreas Fault. Additionally, the wrench tectonics of the San Andreas Fault affected sedimentation by changes the rates of uplift and subsidence in the different parts of the basin which in turn created abrupt facies changes (Graham and Williams, 1985). This implies that some sections of the Monterey formation can have different amount and type of sediments than others. For example, inner basins have more terrigenous sediments than outer basins.

Figure 2.4 San Joaquin Basin Representation. Area being analyzed in this study is highlighted by red rectangle.
Figure 2.5 depicts the large composition range in the Monterey formation sediments. Despite this large variability in composition, authors such as Wooding and Bramlette (1950) and Pisciotto (1981) have found that a general vertical lithology trend can be established. Wooding and Bramlette (1950) first divided the Monterey formation in three different units: the lower, middle, and upper units. Pisciotto (1981) took a step further and divided the stratigraphic units into calcareous, phosphatic, and siliceous facies. This mixture of lithologies complicates any attempts at interpretations of indirect measurements for physical properties.

![Figure 2.5 Sedimentary composition range in the Monterey formation (Isaacs, 1985).](image)

2.2 Tectonic Overprint
The San Joaquin basin has gone through many changes throughout its history. The basin was initially the south part of the of the Great Valley fore-arc basin during Mesozoic Time (Dickison and Seely, 1979; Ingersoll, 1979) (Figure 2.6). In the early Tertiary, the fore-arc basin became structurally segmented, and the San Joaquin basin resembled a borderland style basin as shown on Figure 2.3. In the Middle Tertiary, the San Andreas transform fault system began its northward movement and the San Joaquin basin began to be gradually isolated from the Pacific Ocean. The northward progradation of the San Andreas Fault system was due to the
northward translation of the Salinian block along the San Andreas. Throughout the Miocene, the basin remained as a residual deep-marine basin and eventually filled with sediment and became alluvial in character (Graham and Williams, 1985).

Figure 2.6 Geologic Map of California displaying some of the main Mesozoic tectonic elements (Ring and Brandom, 1994).

The tectonic changes associated with the change from a convergent to a transform boundary not only change the structural style coastal California, but also affected the sedimentation patterns. For example, with the development of the borderland basin style (Figure 2.3). Some of the basins were surrounded by submerged banks or insular terrain and therefore isolated from the North American mainland and its clastic input. Additionally, during the middle to late Miocene, climatic changes led to acceleration in diatom productivity and with this pelagic and hemipelagic sedimentation processes dominated in this time period.

The wrench tectonics of the San Andreas Fault controlled the bathymetric relief and rapid rates of uplift and subsidence (Graham and Williams, 1985). Leading to abrupt and complex changes in facies as compared to other tectonic settings. These abrupt changes have led to a great variation in rock types and identifying the most prolific zones is a challenge.
3. LITERATURE REVIEW

Diagenetic processes alter the mineralogy and, with it, physical properties of the resulting rocks. As a consequence, the Monterey formation exhibits a wide range of lithologies due to both the original composition of the siliceous sediments and due to their subsequent changes during burial diagenesis. The Monterey formation sediments began as biogenic calcareous and amorphous siliceous oozes with varying amounts of detrital material. With increasing burial, the amorphous silica (Opal-A) in the diatoms converted first to a partially ordered crystallite form called Opal-CT and then to well-ordered quartz (Pisciotto, 1981b). The carbonate component originated as calcitic benthic and pelagic foraminifera and nannofossils (Pisciotto, 1981b). During burial some of the calcite was dissolved and reprecipitated as disseminated dolomite rhombs and as dense dolomite beds. The detrital material consists primarily of clay, feldspar, and quartz (Isaacs, 1980). Authigenic phosphate also formed in the organic rich mudstones during shallow burial diagenesis (Garrion et al. 1987). In the following, I document each mineral alteration separately.

Given the large mineralogical variation observed in the Monterey formation rocks (Figure 2.5), such alterations and diagenesis of the different mineral components are critical to understand when evaluating their log response.

3.1 Silica Diagenesis

Silica content in the Monterey Formation is unique, interesting, and intriguing. The silica originated as biogenic Opal-A (also known as hydrous silica), which was deposited in diatom frustules (Keller and Isaacs, 1985). The Opal-A undergoes diagenesis with increasing burial depth and temperature until it transforms into a metastable Opal-CT (Figure 3.1), and later to a stable quartz form (Keller and Isaacs, 1985). This diagenetic process involves changes the structure of the material, which leads to differences in their physical properties. For example, diagenesis of the hydrous Opal-A silica to Opal-CT leads to changes in porosity and density (Isaacs, 1983).
Along with increase of burial depth and temperature, bulk composition plays an important role in silica diagenesis. Figure 3.2 shows the effect of detrital content on the temperatures of silica diagenesis. In the transformation of Opal-A to Opal-CT, the higher the detrital content, the higher the temperatures needed to change to a different phase. Whereas in the transformation from Opal-CT to quartz, the higher the detrital content the lower temperature needed to change. The derived values are 40-50 °C and 0.5-0.2 km for Opal-A to Opal-CT, 65-80 °C and 1.5-3 km for Opal-CT to quartz (Pisciotto, 1981; Keller and Isaacs, 1985). Although this diagram is helpful in representing the transformation of silica to different phases and the factors affecting this transformation, it does not explain the effects of interbedded lithologies. For example, Isaacs (1982) show that the silica phase transformation occurs across a broad, up to 300 m thick, transition zone of interbedded lithologies containing different silica phases. Further investigations on the impact of other sediment types on the rate of diagenesis showed that the transition of Opal-A to Opal-CT is impeded while the Opal-CT to quartz transition is accelerated with an increase in detrital, clay rich sediments (Williams et al. 1985, Figure 3.2 from Behl, 1999). Thus, it is important to study not only at the effects of detrital content but also of organic matter on the properties of the rocks.
Effects on Porosity and Density

Silica alterations are associated with considerable porosity changes (Figure 3.3). Behl (2012) estimated that diatomites will start with a porosity = 80% and grain density = 1.8 g/cm³. As the sediment transforms into Opal-CT, porosity reduces to 15% and density increases to 2.3 grams/ cm³. Finally, in the last stage of transformation to chert, porosity further decreases to 3% accompanied by a grain density of 2.7 grams/cm³. 85% of the original water is estimated to be lost in this process. However, due to varying proportions of detritus content in the basins, the porosity reduction with diagenesis might not be encountered everywhere in the Monterey formation. Chaika et al. (1997) show examples of porosity variation and their implications for seismic properties for outcrop samples from Point Pedernales, and cores from North and South Belridge, Cymric, Elk Hills, and Asphaltto fields.
Figure 3.3 Changes in physical properties for pure and impure diatomites as they go through diagenesis. Pure diatomite leads to chert while impure diatomite leads to porcelanite (modified from Behl, 2012).

Chaika (1998) divided the Monterey formation rocks into two main groups: Group 1 from Elk Hills, Belridge, Cymric, and Asphalto fields had lower Opal (Opal-A and Opal-CT) fractions, higher clay content and higher fractions of non-silica minerals, along with higher bulk density, and lower porosity. The porosity decrease was in Group 1 was explained by an increase in pore-filling, non-silica minerals. In Group 2 rocks (from Point Pedernales and McKittick fields) Opal-CT (and quartz, if present) increased and non-silica mineral fraction stayed relatively constant (Chaika, 1998). In Group 2 the decrease of porosity is caused by pore-filling silica. The non-silica content versus porosity (Figure 3.4) for the two groups is key to understanding the main differences and implications. Group 1 shows a gradual change in porosity, while Group 2 show a gap between 45 and 53% porosity. Implying that Group 2 has a large separation in porosity and other associated properties of Opal-A and Opal-CT rocks. The Opal-A and Opal-CT rocks in Group 1 can have the same porosity and thus might not be distinguishable based on porosity alone (Chaika, 1998).

Chaika (1998) explained the differences in the two groups based on dissolution and precipitation processes. In Group 1, pore waters are assumed to dissolve Opal-A and deposit clay minerals that fill the pore space with two possible reactions: Continuation of Opal-A to
Opal-CT diagenesis or precipitation of clay minerals. This preferred precipitation of silica or of clay is determined by the pore water chemistry and mineralogy of the Opal-A phase rock (Chaika, 1998). In Group 2, Opal-CT replaces the void space and so diagenesis can proceed. By analyzing the patterns from the two different groups, one can conclude that in the case of Group 1 the precipitation of clay was preferred, which is turn slow down the diagenesis of Opal-A, making the transition less prominent as in Group 2 (Figure 3.4).

Figure 3.4 Graphical representation of the different changes in porosity between Opal-A and Opal-CT as proposed by Chaika, 1998 (Chaika and Williams, 2001).

The two groups identified by Chaika (1998) can have significant implications on reservoir properties and their changes with depth. To that end, it is important to increase the data sampling in these groups. All samples studied by Chaika (1998) had porosities higher than 40%; it is critical to understand the systematics of porosity reduction in lower porosity range. The samples studied in this thesis had porosities below 20%.

Effects on Permeability

Diagenetic changes greatly affect matrix permeability in the Monterey formation. Fluid transport depends not only on the interconnected matrix pore space but also on presence and permeability of fractures. Every rock type of the Monterey formation has varying amount of
fracture permeability. Outcrop studies show that chert, porcelanite, mudstone, and dolostone are characterized by decreasing fracture permeability (MacKinnon, 1989). However, subsurface conditions might present a very different scenario. Although permeability lies outside the scope of this study, development of fractures should be detected by its effect on other physical properties.

Tectonic stresses are some of the biggest factors for variations in fracture density and connectivity. Changes in stress will create fractures and faults across different types of sediments. These fractures or faults can act as barriers or conduits for fluid transport. Eichbul and Behl (1998) matched isotopic composition of carbonates veins to lower sediments. Diagenetic transformations can occur in the fractures as the minerals move to different depths, temperatures, or water of different chemical composition. Such transformations can cement the fractures. Core analysis could help to identify core-scale fractures that appear to be cemented or with traces of hydrocarbons.

Water Content

Migrated formation water is not the only source of water in the Monterey formation. The Monterey formation is made up of different types of sediments such as Opal-A and smectite which are known to release water during diagenesis. Opal-A can contain as much as 17% by weight of water (Hurd and Thevar, 1977). The release of structural water in conversion of smectite to illite can account for 10-15% of its compacted bulk volume (Burst, 1969). This released water can migrate to other zones through pathways, such as permeable fractures and affect resistivity or water production.

3.2 Smectite to Illite Transformation

Despite marine depositional setting, the Monterey sediments still received terrigenous sediment influx. The young sediments contained mainly smectite minerals. With increasing depth, the smectites alter to illite. This smectite to illite transformation is considered to be one of the fundamental reactions in clastic diagenesis. The diagenetic formation of illite first involves the formation of series of increasingly illitic mixed-layer illite/smectite (I/S). This
transformation has been linked to burial parameters such as temperature, time, and fluid composition. Using studies from offshore and onshore basins, Abercrombie et al. (1994) have suggested that smectite-illite reaction occurs as a result of a reduction in silica activity which is marked by the onset of quartz precipitation.

Ramseyer and Boles (1986) pointed out that that the data collected can be divided into two groups. The first group consists of oil fields that have undergone relatively slower burial and therefore have had longer residence times within a temperature window. The second group represents oil fields that have undergone faster burial and therefore shorter residence times in a temperature window.

![Figure 3.5](image1.png)

**Figure 3.5** Figure A represents the expandability of I/S versus temperature (Ramseyer and Boles, 1986) in Group I is data from oil fields with longer residence times over a particular range during burial. Group II is data from oil fields with shorter residence.

Figure 3.5 shows the different silica activity versus temperature trajectories followed by Groups I and II. The silica activities in Group I waters are close to amorphous silica saturation at approximately 40 degrees Celsius and decline to Quartz by 100 °C. In the case of Group II, the values stay at higher temperatures and do not decline to quartz saturation until 150 °C.
same trend can be observed from the case of I/S expendabilities for Groups I and II. For Group I which reaches quartz saturation by 100 C, the I/S reaction begins at approximately 100 C and reaches completion by 120°C. In the case of Group II, I/S reaction begins at 120°C and reaches completion by 150°C. Based on this, Abercrombie et al. (1994) suggested that the smectite to illite reaction is driven by the reduction of pore-water silica activity.

Understanding the transformation of smectite to illite can also be important when trying to estimate water saturations in the Monterey formation. For example, the smectitic clays that are commonly present in sediments have interlayer water associated with them. However as the smectite transforms to illite, this water is released (Passey et al. 2010), thus increasing the water volume present in other pores. This highlights the importance of understanding diagenetic processes. It also shows that seemingly disparate processes can actually be dependent on one another. Silica activity and I/S transformation have an effect on one another.

The total organic content (TOC) content in the Monterey Formation represents a paradox (Passey et al. 2012). This is due to the fact that intervals that seemed to have the most enriched organic matter do not correspond with the zones that have been estimated to have the highest organic matter production rate. The input for most of the organic matter is diatoms (Bohacs, 1990) controlled by primary organic production. However, sections with the highest sediment accumulation do not have the highest organic content. These sections are dominantly cherty and have little organic matter (Passey et al. 2012). Implying that in places like the Monterey formation where organic matter enrichment occurred in a mostly biogenic and distal setting, autodilution of organic matter from biogenic material can be an important factor in organic matter accumulation (Tyson, 1995, 2001).

Most of the studies have been performed for coastal areas in California; a direct comparison to more central basins such as the San Joaquin Basin can be very complex. However, it can still be assumed that overall most of the sediments deposited have gone through similar changes.
3.3 Organic Matter

The distribution of organic matter in the Monterey formation is closely related to the regional setting. This setting has been described as a fault-bounded continental borderland basin where sediments were deposited in relatively calm and deep waters. However, with time the deep waters became shallower and the deposited sediments became exposed to a higher energy setting (Gorsline and Emery, 1959; Isaacs et al. 1996; Schwalbach and Bohacs, 1996). Overall the system evolved from a sedimentation scenario in which sub basins were each isolated by intervening highs to a scenario in which sediment where broadly deposited and significant strata thinning occurred (Schwalbach and Bohacs, 1996).

In such a setting, most of the terrigenous clastics must have been deposited in basins near the shore; the outward basins would be starved of terrigenous clastic. However, a perfect combination of climate and ocean conditions created an increase in planktonic production in surface waters. This planktonic production was both siliceous and calcareous and it created oxygen depleted zones in deep waters (Pisciotto and Garrison, 1981). It was under these biogenic conditions that sediments were deposited and accumulated.

Berger and Kerr (1984) showed that siliceous material dominates at high rates of planktonic production (diatoms), while calcareous material (cocolithophores) dominate in the intermediate to low rates of production. Terrigenous detritus influx rates are the highest during low sea level intervals.

Organic Matter Production

The quality of the source rocks of the Monterey Formation are thought to be a function of the total organic carbon (TOC), oil-proneness or hydrogen content, and sulfur content of the oil (Bohacs, 1993). The estimated high levels of organic production throughout the Monterey formation, however do not seem to be have a significant correlation with the source quality.

Figure 3.6 shows that there is little to no correlation between TOC and biogenic silica. The results by Bohacs et al. (2005) are surprising since most of the organic matter should come from siliceous diatoms. This can indicate that other factors are contributing to the TOC content observed in the rocks.
Bohacs et al. (2005) also showed that TOC content does not have a clear correlation with the estimated rates of primary organic-matter production (Figure 3.7). This lack of correlation between TOC and primary organic-matter production indicates that processes such as destruction and dilution can also affect TOC values. The organic richness in the sediments can be decreased or diluted by an increase in biogenic silica deposition or by an increase in influx of clastics.

Figure 3.6 Poor to no relationship between biogenic silica and TOC in the Monterey formation (Bohacs et al. 2005).

Figure 3.7 Lack of correlation between TOC and estimated primary production rates of primary organic matter (Bohacs et al. 2005).
Destruction and Dilution

Figure 3.8 shows the relationship between TOC and detritus content from outcrop samples from the Santa Maria basin (Bohacs et al. 2005). Two different processes are thought to govern the TOC-detritus content relationship. Below the 50% detritus content, there is a strong positive correlation between detritus content and TOC. This is possibly due to increased detritus as a result of better transport and better burial efficiency. At detritus content larger than 50% the relationship is reversed. This decrease in TOC is due to dilution by terrigenous non-organic material (Bohacs et al. 2005).

![Figure 3.8 Differences in relationship between TOC and detritus content. Up until 50% detritus content there is a strong positive relationship, however after 50% detritus content there is an inverse relationship between the two parameters (Bohacs et al. 2005).](image)

Thus, the accumulation and maturation of organic matter in sediments is complex and it involves interactions with other processes (Bohacs, 2005). In order to identify zones with the highest potential to contain organic matter one must take into account all of its components from the environment of deposition, structural development, mineralogy, to diagenetic changes in each constituent.
3.4 Log Analysis

The Monterey formation is often called a shale, however the rocks from this formation are not shales but mixtures of different types of lithologies, such as siliceous shale, chert, diatomite, opaline, limestone, sand, dolomite and clay. Additionally, the thickness in each of the beds can vary from only millimeters to several feet (Cannon, 1981). This greatly complicates any type of conventional log analysis. However, in order to develop such methods one must understand its current applications and pitfalls.

3.4.1 Standard Logs

Despite the unconventional nature of the Monterey formation, the standard logging suites still have a significant amount of application in characterizing matrix rock properties. For example, a basic log suite of neutron, density porosity, and gamma ray are sufficient for estimating silica phase and clay volume. The latter parameters are very important in determining matrix reservoir quality. However, the limiting factor is that the tool resolution can be not enough to detect the thin beds encountered in the formation.

3.4.2 Specialized logs

Non-standard logs such as spectral gamma ray have proved to be beneficial in the Monterey formation. For example, a common problem in the Monterey formation was the high gamma ray response in zones that did not seem to have high clay content. The spectral gamma ray log that measures the three primary gamma radiation components which are uranium, potassium, and thorium; proved useful here. In the case of the Monterey formation obtaining information about the uranium content can be very beneficial because as demonstrated in outcrop and core analysis, it has a high correlation with organic matter (Schwalbach, 1992; Schwalbach and Bohacs, 1992a). Additionally, the abundances of these elements vary systematically with some key stratigraphic elements (Schwalbach and Bohacs, 1992a, 1992b, 1996)).

3.4.3 Image Logs

Fractures play a very important role in the productivity of Monterey rocks. This is very apparent when examining outcrops in the coastal area of California. In many cases, these
outcrops are highly fractured and filled with tar or have hydrocarbon stains. Cores that are obtained from the subsurface usually have micro fractures and it is also typical to encounter mud losses during drilling operations (Schwalbach, 1992). Image logs have proven to be very beneficial as they provide direct observations of fractures and faults in-situ.

Figure 3.9 show the range and median value of fracture density obtained from cores and outcrops from the different rock types in the Monterey formation. It helps to show that the mineral composition of the rock can control the fracture densities and provide a wide range of values in each of the rock types.

![Figure 3.9 Bar chart illustrating the range and median value of fracture density measured from cores and outcrop data in the different Monterey rock types (modified from Schwalbach, 1992).](image)

3.5 NMR Measurements

The T$_2$ decay curve in Figure 3.10 is the addition of the T$_2$ signals from independently relaxing protons that are under different conditions and in different pore spaces. Generally, it is
assumed that the shortest $T_2$ are associated with the clay bound water in the cores, medium $T_2$ to capillary bound water and $T_2$ is related to free or producible fluids. These parameters will be of importance to our studies and so we have decided to concentrate on obtaining $T_2$ signals for our cores.

As it can be seen from Figure 3.10 the first step in NMR $T_2$ analysis is obtaining the $T_2$ decay curve. This measured signal is represents the superposition of all decaying signals as a spectrum. By using a mathematical inversion the signal is decomposed into its individual components and plotted as a $T_2$ distribution. From this point the curve can be divided into different components that are attributed to different pore size distributions (Westphal et al. 2005).

![Diagram of NMR processing and analysis steps](image)

**Final step**

Figure 3.10  Steps taken during NMR processing and analysis. (A) Is the echo train or $T_2$ decay curve, which is in the acquisition time domain. (B) $T_2$ spectrum that is obtained after the inversion process; this data is in the relaxation time domain. (C) $T_2$ spectrum can be divided into clay bound water; capillary bound water, and free movable water. The division comes from different $T_2$ cutoffs (modified from Westphal et al. 2005).
4. METHODS AND MATERIALS

The study area lies in the San Joaquin Basin, California (see Figure 4.1 for location). The USGS has estimated that the San Joaquin Basin has 1.8 trillion cubic of gas (TCFG) and 393 million barrels of oil (MMBO). Some of the fields that currently under production are Coalinga, Lost Hills, North and South Belridge, Elk Hills, Kern River, Mount Paso, Cymric, Buena Vista, and Midway Sunset.

For this study a total of three wells will be analyzed. Wells 1, 1B, and 2 come from the shallowest section of the San Joaquin Basin, in close proximity to Midway Sunset field (Figure 4.1). One particular challenge is that none of the core samples have been preserved; they have been cleaned with toluene.

Figure 4.1  Map of California showing Los Angeles Basin, coastal basins, San Joaquin Basin, and outlines the giant fields. Area of study for this research is the San Joaquin Basin and is marked by the purple rectangle in the figure (modified from http://energy.cr.usgs.gov/regional_studies/pacific).
4.1 Materials

The available log and core data available for this study cover the Gould, Devilwater, McDonald, and Antelope Members of the Monterey formation. A total of 19 core samples from two wells were available for this study. The core samples come mainly from the Gould, Devilwater, McLure, and Antelope members of the Monterey formation (Figure 4.2). The depths vary from 5000 to 9000 ft (Figure 4.2).

4.1.1 Core Inventory

I studied a total of 19 core samples for their ultrasonic and NMR properties. The mineralogical compositions of the samples used for this study are summarized in Table 4.1 and Table 4.2. The mineralogy data was acquired by a commercial vendor (Corelab). For well 1, the X-Ray Diffraction Data (XRD) was not available for the exact samples studied here. However, XRD data was available for cores in close proximity to the samples used (for example, core 7220.8′, 7226.3′, and 8154.5′). I checked the applicability of the XRD measurements for samples taken within the same interval as the XRD data by comparing core photos of the entire cross section with the available core samples. Of course, it is possible that despite the close proximity there might be discrepancies due to thin layers.

Table 4.1 Conventional Core X-Ray Diffraction data available for Well 1. NA represents not available data.

<table>
<thead>
<tr>
<th>Available Core Plug Depth (ft)</th>
<th>Analyzed Core Plug Depth (ft)</th>
<th>Bulk Mineralogy (Weight %)</th>
<th>Clay Mineralogy (Relative Weight %)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Quartz</td>
<td>Plagioclase</td>
</tr>
<tr>
<td>7220.8</td>
<td>7220.75</td>
<td>69</td>
<td>6</td>
</tr>
<tr>
<td>7223.7</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7226.3</td>
<td>7225</td>
<td>67</td>
<td>2</td>
</tr>
<tr>
<td>7238.2</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7750.8</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7751.8</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8154.5</td>
<td>8154.15</td>
<td>68</td>
<td>6</td>
</tr>
</tbody>
</table>

In the case of well 1B, a total of 12 samples were available for measurements. These samples were picked to represent a wide range of lithologies. As seen from Table 4.2, all samples except for 8272′ had XRD data available. There is a wide variation of mineralogy in the samples, for example the sample at 5360′ has a quartz content of 83.6% quartz, while sample
8539’ is 91.5% dolomite. There is also a variation in the clay content, the minimum clay content was 0% (sample 8539’) and the maximum was 41.8% (sample 8288’).

Table 4.2 Rotary Sidewall Core X-Ray Diffraction Data Available for Well 1B.

<table>
<thead>
<tr>
<th>Core Depth (ft)</th>
<th>Bulk Mineralogy (Weight %)</th>
<th>Clay Mineralogy (Relative Weight %)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Quartz</td>
<td>Plagioclase</td>
</tr>
<tr>
<td>5360</td>
<td>83.6</td>
<td>0.7</td>
</tr>
<tr>
<td>5440</td>
<td>55.2</td>
<td>0.5</td>
</tr>
<tr>
<td>7906</td>
<td>59.2</td>
<td>1.8</td>
</tr>
<tr>
<td>8272</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>8288</td>
<td>39</td>
<td>3.2</td>
</tr>
<tr>
<td>8333</td>
<td>77.5</td>
<td>1.3</td>
</tr>
<tr>
<td>8539</td>
<td>8.1</td>
<td>0</td>
</tr>
<tr>
<td>8612.2</td>
<td>50.4</td>
<td>5.2</td>
</tr>
<tr>
<td>8935.1</td>
<td>77</td>
<td>1.8</td>
</tr>
<tr>
<td>9097</td>
<td>71</td>
<td>3.3</td>
</tr>
<tr>
<td>9193</td>
<td>72.6</td>
<td>3.6</td>
</tr>
<tr>
<td>9447.5</td>
<td>10.6</td>
<td>0</td>
</tr>
</tbody>
</table>

Porosity, permeability, and saturation data from a commercial vendor (Corelab) was also available (Table 4.3 and Table 4.4). For several core samples in well 1 (Table 4.3), the data does not correspond to the cores available. As before, by comparing core photos of the entire cross section with the available core samples, I checked the applicability of the data by determining that the core samples were taken from the same interval.

Table 4.3 Porosity, permeability, and saturation data available for Well 1. F/ implies a visible fracture on the core sample.

<table>
<thead>
<tr>
<th>Core depth available for thesis analysis</th>
<th>Depth used for analysis</th>
<th>Permeability (kair)</th>
<th>Porosity</th>
<th>Fluid Saturation</th>
<th>O/W Ratio</th>
<th>Total</th>
<th>Grain Density</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ft</td>
<td>Fracture</td>
<td>md</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>7220.8</td>
<td>7221</td>
<td>0.31</td>
<td>5.4</td>
<td>41.8</td>
<td>55.9</td>
<td>0.78</td>
<td>99.7</td>
</tr>
<tr>
<td>7223.7</td>
<td>7224</td>
<td>1.69</td>
<td>2.8</td>
<td>31.7</td>
<td>68.1</td>
<td>0.47</td>
<td>99.8</td>
</tr>
<tr>
<td>7226.3</td>
<td>7226.1</td>
<td>f/</td>
<td>3.331</td>
<td>3.2</td>
<td>40.5</td>
<td>58.8</td>
<td>0.69</td>
</tr>
<tr>
<td>7228.2</td>
<td>7228.1</td>
<td>0.25</td>
<td>6</td>
<td>48.1</td>
<td>40</td>
<td>1.2</td>
<td>88.1</td>
</tr>
<tr>
<td>7750.8</td>
<td>7751</td>
<td>0.02</td>
<td>4.5</td>
<td>37</td>
<td>61.2</td>
<td>0.6</td>
<td>98.2</td>
</tr>
<tr>
<td>7751.8</td>
<td>7751.7</td>
<td>1.084</td>
<td>20</td>
<td>60.2</td>
<td>23.7</td>
<td>2.54</td>
<td>83.9</td>
</tr>
<tr>
<td>8154.5</td>
<td>8154.3</td>
<td>0.015</td>
<td>1.6</td>
<td>58.9</td>
<td>40.3</td>
<td>1.46</td>
<td>99.2</td>
</tr>
</tbody>
</table>

For well 1B, of the 12 samples available, only nine samples had permeability, porosity, and saturation data available. This type of data will be very beneficial as we will be able to
compare the porosity from NMR measurements to that obtained by porosimetry measurements from Corelab (Table 4.3 and Table 4.4).

Table 4.4 Porosity, permeability, and saturation data available for Well 1B. F/ represents visible fractures in the core sample.

<table>
<thead>
<tr>
<th>Depth (ft)</th>
<th>Length</th>
<th>Permeability</th>
<th>Porosity</th>
<th>Fluid Saturation</th>
<th>O/W Ratio</th>
<th>Total</th>
<th>Grain</th>
<th>Kair</th>
</tr>
</thead>
<tbody>
<tr>
<td>in</td>
<td>Fracture</td>
<td>md</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>g/cc</td>
<td>g</td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>-----------</td>
<td>-----------------</td>
<td>----------</td>
<td>------------------</td>
<td>-----------</td>
<td>-------</td>
<td>-------</td>
<td>------</td>
</tr>
<tr>
<td>5440</td>
<td>1.5</td>
<td>F/</td>
<td>4.4</td>
<td>12.8</td>
<td>15.8</td>
<td>72.1</td>
<td>0.22</td>
<td>87.8</td>
</tr>
<tr>
<td>7906</td>
<td>1.3</td>
<td>F/</td>
<td>4.3</td>
<td>5.6</td>
<td>30.7</td>
<td>60.3</td>
<td>0.51</td>
<td>98</td>
</tr>
<tr>
<td>8288</td>
<td>1.5</td>
<td>F/</td>
<td>3.4</td>
<td>5.8</td>
<td>31.2</td>
<td>53</td>
<td>0.59</td>
<td>84.1</td>
</tr>
<tr>
<td>8333.2</td>
<td>1.7</td>
<td>-</td>
<td>0.106</td>
<td>2</td>
<td>11.6</td>
<td>86.4</td>
<td>0.13</td>
<td>98</td>
</tr>
<tr>
<td>8539</td>
<td>1.6</td>
<td>-</td>
<td>0.066</td>
<td>1.5</td>
<td>9.4</td>
<td>16.6</td>
<td>0.57</td>
<td>26</td>
</tr>
<tr>
<td>8632.2</td>
<td>1.9</td>
<td>-</td>
<td>0.025</td>
<td>1.7</td>
<td>6.8</td>
<td>89.3</td>
<td>0.08</td>
<td>96.1</td>
</tr>
<tr>
<td>9097.1</td>
<td>1.6</td>
<td>-</td>
<td>0.013</td>
<td>1</td>
<td>22.9</td>
<td>60.4</td>
<td>0.38</td>
<td>83.2</td>
</tr>
<tr>
<td>9193.1</td>
<td>2</td>
<td>-</td>
<td>0.013</td>
<td>2.1</td>
<td>11</td>
<td>87</td>
<td>0.13</td>
<td>98</td>
</tr>
<tr>
<td>9447.5</td>
<td>1.7</td>
<td>-</td>
<td>0.038</td>
<td>1</td>
<td>22.7</td>
<td>59.9</td>
<td>0.38</td>
<td>82.6</td>
</tr>
</tbody>
</table>

Table 4.5 shows a summary of the core analyzed, type of experiment performed, and any problems encountered.

Table 4.5 Summary of the samples and type of experiments performed for the study for Well 1.

<table>
<thead>
<tr>
<th>Depth (ft)</th>
<th>Pressurized Ultrasonic</th>
<th>NMR</th>
<th>Spectral Induced Polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td>5477.3</td>
<td>NA</td>
<td>x</td>
<td>NA</td>
</tr>
<tr>
<td>7220.8</td>
<td>Broken</td>
<td>x</td>
<td>NA</td>
</tr>
<tr>
<td>7223.7</td>
<td>x</td>
<td>NA</td>
<td>v</td>
</tr>
<tr>
<td>7228.2</td>
<td>x</td>
<td>x</td>
<td>v</td>
</tr>
<tr>
<td>7626.3</td>
<td>x</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>7750.7</td>
<td>x –Partly Broken</td>
<td>x</td>
<td>v</td>
</tr>
<tr>
<td>7751.8</td>
<td>x</td>
<td>x</td>
<td>v</td>
</tr>
<tr>
<td>8154</td>
<td>x - Leak</td>
<td>x</td>
<td>v</td>
</tr>
</tbody>
</table>

X =experiments done, v= completed but not used in this study, NA = not available
Table 4.6 Summary of the samples and type of experiments performed for the study for Well 1.

<table>
<thead>
<tr>
<th>Depth (ft)</th>
<th>Benchtop Ultrasonic Dry (Vp &amp; Vs) (0 &amp; 90°)</th>
<th>NMR Dry</th>
<th>NMR Saturated</th>
</tr>
</thead>
<tbody>
<tr>
<td>5360</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>5440</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>7906</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>8272</td>
<td>Broken</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8288</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>8333</td>
<td>NA</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>8539</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>8632</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>8935</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>9097</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>9193</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>9447.5</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

X = experiments done, NA = not available
Figure 4.2 Stratigraphic column, spectral and total GR of Wells 1 and 1B showing position of available core data.
4.1.2 Log Inventory

Table 4.7 Summary of log data available for the three different wells used in this study.

<table>
<thead>
<tr>
<th>Well</th>
<th>Spectral Gamma Ray</th>
<th>Bulk Density, RHOB</th>
<th>Resistivity</th>
<th>Neutron Porosity, NPHI</th>
<th>Combinable Magnetic Resonance, CMR</th>
<th>Compressional Travel Time, DTC</th>
<th>Elemental Capture Spectroscopy, ECS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well 1</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Well 1B</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Well 2</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

4.2 Experimental Procedure

In the following, I will describe the experiments performed on core samples namely ultrasonic and NMR experiments. The ultrasonic measurements were made at two conditions: at benchtop and under changing confining pressure. Only benchtop measurements were possible on core samples that had a length limitation (less than 0.9 inches). The pressurized ultrasonic measurements were made on cores longer than 1”.

4.2.1 Ultrasonic Measurements

Ultrasonic velocity measurements were performed using a pulse transmission method. In this method, a generator generates electrical pulses that are converted by a piezoelectric transducer into elastic waves. The wave then travel through the core sample and the signal is received on the opposite end by another transducer. The receiver transducer transforms the elastic wave into an electric pulse that is then recorded by a digital oscilloscope. Using an in-house SpectrumDivision program, the wave is recorded from the oscilloscope and the velocity and other signal attributes are calculated.

4.2.1.1 Benchtop Measurements

Ultrasonic travel time measurements at benchtop conditions were made on all 19 available samples from well 1B. Compressive and shear-wave velocities were made using the following formula:
Where, \( V \) is the velocity, \( L \) in this case is the diameter of the sample, and \( T \) is the recorded travel time. Figure 4.3 shows the typical benchtop assembly that was used for acoustic measurements.

As shown in Figure 4.3, for benchtop measurements the surface of the transducers are placed directly on the core. This can create a source of error because some samples contain fractures or the sides were not completely flat. Precaution was taken in order to have flat surfaces. Thus, some of the surfaces were made flat by filling down the sides. Acoustic coupling was used to obtain a good connection between the transducer and the core.

Pressurized Measurements

Seven samples were prepared for pressurized measurements. Although, the samples were prepared for ultrasonic measurements as well as conductivity measurements, the conductivity measurements will be part of future studies (Figure 4.4). Pressurized ultrasonic measurements have several applications. For example they can be used for core to log correlations and to develop depth and compaction trends. The behavior of velocity as pressure
increases can give us an idea on the pore geometry. For example Punto et al. (2005) studied the pressure dependence of silicate and calcite rocks from the Peloritani Mountain Belt. They found that an increase in confining pressure leads to a non-linear increase in the P- and S-wave velocities. The transition from non-linear to linear behavior is attributed to the “crack closing pressure”. The linear section in the graphs represents the intrinsic velocity of the compacted aggregate. Additionally, it is important to point out that overall the increase in linear velocities are much higher in silicate rocks than in calcite rocks. It will be important to keep this in mind when analyzing zones that have high calcite content.

Additionally, the recorded ultrasonic wave date, which is recorded in a plot of amplitude versus time, can be transformed into frequency versus time by using Fourier transform. This data can then be investigated to see if any pressure dependence exists in the frequency domain.

Sample Preparation

The preparation of the samples started by first cutting the samples to make sure that the end surfaces were completely flat. Ultrasonic P and S crystals were cut to size of about 3 mm by 5 mm rectangles. In order to account for the anisotropy of the rock sample, the ultrasonic crystals were placed at 0 and 90 directions. These angles will constitute the naming convention from now on through the rest of this text. \( V_{p90} \) denotes a measurement performed in the direction perpendicular to the direction with the highest recorded velocity (called \( V_{p0} \)). In Vivo Metric 50 E205 Ag-AgCl electrodes were placed on the same direction as the P- and S-wave crystals. The bonding between the crystal and electrodes with the core was done by using silver conducting epoxy. The silver conducting epoxy is used to couple the system and ground the electrical circuit. Once the core had been prepared and signals recorded the next step was to place the sample on core holders and seal it on the sides by using an epoxy jacket. The epoxy is a flexible polymer that is made by Resinlab. This jacket has two purposes; first it helps as a way to separate the confining oil from the sample and second to control the pore pressure in the sample.
Figure 4.4 Example of core sample assembly for acoustic properties at different angles.

Figure 4.5 shows a sketch of the core assembly and an example of a prepared core. Perhaps one of the biggest concerns of using this experimental set up is that the epoxy used to seal the core can act as a shield to the confining pressure that is applied using a Isco pump. The measurements were made at various steps in ambient and dry conditions. The maximum confining pressure was determined by integrating the bulk density log. A safety factor of 200 psi was used to make that the core was not over pressurized.

Figure 4.5  A) Shows a schematic of the sample core assembly (modified from Woodruff, 2012).  
B) Shows an example of the final core assembly.
Details on the sample core assembly are given in the Appendix A; Section Sample Core Assembly.

Velocity was measured during pressure loading and unloading. Additionally, the signals were recorded using 10 us/div and 4 or 2 us/div.

4.2.2 NMR Measurements

For this experiment a Magritek 2MHz core analyzer has used to measure the NMR signal. This instrument has the capability to measure both longitudinal and transverse relaxation times and create 2D correlation maps. However, for this study we will only concentrate on the transverse ($T_2$) relaxation time. The $T_2$ relaxation time is a result of a mathematical inversion of the decay time. NMR and $T_2$ responses are based on different fluid types and properties of the porous material such as pore size distribution and wettability (Coates et al. 1999). As mentioned earlier, for this study we will only concentrate on the pore size distribution of the rocks as the wettability may have been compromised as the cores where cleaned by different chemicals. For example Anderson (1986) reported that the use of chemicals such as toluene, chloroform, and methanol can change core wettability from neutrally wet or mildly oil-wet to strongly water-wet. Therefore, wettability studies based on NMR should be made on native-state cores.

Methodology

For this experiment two measurements were made. The first experiment was done after drying the samples had been properly dried and all the respective parameters had been measured. This measurement does not seem very logical because the hydrogen atoms would be gone after properly drying the sample. When clays are present in the core they retain water even at high temperatures. NMR experiments of dry samples allow us to check if any clay bound volume can be identified. The problem with this type of experiment is that in the processes of obtaining the NMR signal the sample is exposed to the atmosphere and depending on the humidity conditions in the lab, it could pick up hydrogen from the atmosphere. Another
problem is that dry samples tend to have a very strong background signal, which means that distributions that might seem properties of the rock could actually end up being background noise. In order to help alleviate this problem a background correction using an empty probe was made.

For the second set of experiments, the cores were saturated using a brine solution. The brine salinity (20,000 ppm) matched the average salinity determined from different formation fluid test. The samples were saturated for a total of two weeks under 600 psi pressure. More specifics on the measurements can be found in the appendix section. After saturation, NMR signals were obtained for each sample. The acquisition parameters for the measurements include number of scans, pulse length, number of echoes, and echo time. The parameters can be adjusted to change the information content of acquired data. A background signals is also obtained after this set of experiments as the laboratory conditions might have changed during the period of saturation of the cores.

The next step was to run an NMR experiment on the bulk fluid. This experiment was the longest (2 hours compared to 5 mins for core samples) as the bulk fluid has a longer relaxation time. A critical aspect of this step is to ensure that the volume of fluid used to obtain the signal is known with a good precision. In this case, 25 ml (of the 20,000 ppm salinity brine) was measured using a pycnometer at normal laboratory conditions.

In the NMR experiment, the initial amplitude of the raw decay curve can be directly proportional to the number of hydrogen nuclei that have been polarized in the pores (Figure 4.6). Therefore, the amplitude can be calibrated to porosity by using the NMR signal from the known volume of the bulk fluid.

As mentioned earlier in this study we will concentrate on NMR $T_2$ distribution. The $T_2$ distribution is formed by a set of decay constants that can be fit by a sum of decaying exponentials. In water saturated rock the decay curve associated with a single pore will be a single exponential that has a decay constant proportional to its pore size (Coates et al. 1999). In general, small pores have small $T_2$ values and large pores have large $T_2$ values. For a core
sample, we will obtain a multi-exponential decay representing a distribution of pore sizes for that particular depth.

![Graph showing decay of a spin-echo train](image)

**Figure 4.6** Decay of a spin-echo train, which is a function of the amount and distribution of hydrogen present. This type of information can be used to establish pore fluid types and pore size distributions. Points are raw data and the line is a fit (Coates et al. 1999).

The area under the curve of a $T_2$ distribution can be linked directly to porosity after calibration. Additionally, because $T_2$ values are related to the pore sizes, a threshold can be established to differentiate between small and large pores. This value is called a $T_2$ cutoff and (see example is given in Figure 4.7). The figure shows that below a fixed $T_2$ value the fluids occupying the small pores spaces will not be able to move (i.e. bound water) and above the $T_2$ the fluids lying in the larger pores will be able to move.
Figure 4.7 Example of a T2 distribution which is observed through a mathematical process of inversion. With the proper calibration the area under the curve of a T2 distribution is equal to porosity. Additionally because the T2 spectrum is related to pore size distribution, a fixed T2 value will show pore sizes for which fluids below this level will not be able to move and for which above they will be able to move (Coates et al. 1999).

One of the current problems in the industry is that a fixed T2 value is used for all types of lithologies and fluids. However, as it can be expected, different pore types and lithologies will have different T2 cutoffs. For example, in clastics the cutoff is 33 ms and for carbonates is 90 ms (Coates et al. 1999).

4.2.3 Log Analysis and core to log comparison
One of the main goals for the log analysis is to be able to compare the data recorded in the laboratory and that recorded by logging tools. The main logs that will be analyzed here are travel times and CMR.
In order to compare ultrasonic measurements with sonic logs, several factors must be taken into account. First, the frequency for ultrasonic measurements is about 0.5 MHz or more, while for sonic frequency is in the range of 10 kHz. The measurements of samples from Well 1B were performed at benchtop conditions while the logging data shows the effect of pressure. We will investigate the effect of pressure on the cores with measurements performed at pressurized measurements. Lastly, the ultrasonic measurements were performed on dry samples and sonic logging data shows the effect of fluid saturation. The dry rock velocities can be converted to saturated rock data using Gassmann fluid substitution (Gassmann, 1951).

The data from the dry samples are mathematically saturated by using P-wave (M) modulus approximation provided by Mavko et al. (1995). This methodology is used since for samples from Well 1B only compressional velocity is available. This method is based on the fact that the bulk modulus in Gassmann’s relationship can be replaced by the M-modulus. The equation for M-modulus is as follows:

\[ \text{M}_{\text{dry}} = \rho V_p^2 \quad \text{(Mavko et al. (1995))} \]

Where \( \rho \) is the grain density in g/cm\(^3\), and \( V_p^2 \) is the compressional velocity in (km/s).

The equation used to calculate the M-modulus is as follows:

\[
M_{\text{sat}} = (M_s) * \left( \frac{\phi M_{\text{dry}} - (1 + \phi)K_f M_{\text{dry}} + K_f}{(1 - \phi)K_f + \phi M_s - \frac{K_f M_{\text{dry}}}{M_s}} \right) \quad \text{(Chaika, 1998)}
\]

Where \( M_{\text{sat}} \) and \( M_s \) (calculated using Voigt, Reuss, and Hill average) are the saturated solid M-modulus, respectively. \( K_f \) is bulk density of fluid, in this case brine.
5. RESULTS

Results from ultrasonic experiments at benchtop and pressurized conditions are reported here to identify velocity trends in the Monterey formation. The velocity trends will later be analyzed and compared to data obtained from NMR distributions.

5.1 Benchtop Measurements

Figure 5.1 shows an example of the wave forms obtained at benchtop conditions. Most of the samples are shown in the Appendix; here we only present two examples. Figure 5.1 shows the compressional wave propagation along four different directions for sample 8935 from Well 1B. As described in Chapter 4, the core was physically analyzed (i.e. layering, fractures, etc.) and the direction with the highest (Vp1) and lowest (Vp2) velocities were identified. As seen in Figure 5.1 the differences between each of the velocities is not significant.

![Figure 5.1 Compressional wave propagation along four different directions for sample 8935 in Well 1B. Picture of core is included showing the directions. Dashed line marks the start time.](image-url)
Figure 5.2 shows the compressional wave propagation for sample 7906 from well 1B in four different directions. In contrast to sample 8935, this sample shows a significant change in velocity between Vp1 and Vp2. As it can be seen from the optical image in Figure 5.2 the sample has significant bedding fractures some of which are calcite filled.

![Compressional wave propagation](image)

Figure 5.2 Compressional wave propagation along four different directions for sample 7906 in Well 1B. Picture of core is included showing the directions. Dashed lines mark the start of the start time.

The remaining ultrasonic wave signals can be found in the Appendix A: benchtop signals.

Table 5.1 gives a summary of the compressional velocities along different directions for all of the samples. As it can be observed from Table 5.1, Vp1 or the compressional velocity in the parallel direction (Vp1) has higher velocity values than Vp2 which is the perpendicular direction (Vp2). Additionally, the Vp3 and Vp4 velocities lie in between the Vp2 (minimum) and
Vp1 (maximum). The only exception is sample 8288 which has a Vp1 that is almost 4 times bigger than Vp2.

Table 5.1 Summary of compressional velocities obtained for core samples from Well 1B. Vp1 was measured parallel and Vp2 perpendicular to any aligned textures. The velocities were obtained at benchtop conditions.

<table>
<thead>
<tr>
<th>Depth (ft)</th>
<th>Compressional Velocity, Vp2 (km/s)</th>
<th>Compressional Velocity, Vp1 (km/s)</th>
<th>Compressional Velocity, Vp3 (km/s)</th>
<th>Compressional Velocity, Vp4 (km/s)</th>
<th>Average Compressional Velocity, Vp (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5360</td>
<td>3.13</td>
<td>4.00</td>
<td>3.56</td>
<td>3.21</td>
<td>3.47</td>
</tr>
<tr>
<td>5440</td>
<td>3.38</td>
<td>3.44</td>
<td>3.43</td>
<td>3.44</td>
<td>3.42</td>
</tr>
<tr>
<td>7906</td>
<td>3.01</td>
<td>3.89</td>
<td>3.04</td>
<td>3.02</td>
<td>3.24</td>
</tr>
<tr>
<td>8272</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>8288</td>
<td>4.16</td>
<td>1.07</td>
<td>1.59</td>
<td>1.46</td>
<td>2.07</td>
</tr>
<tr>
<td>8333</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>8539</td>
<td>5.76</td>
<td>6.15</td>
<td>5.93</td>
<td>5.26</td>
<td>5.78</td>
</tr>
<tr>
<td>8632</td>
<td>3.33</td>
<td>4.63</td>
<td>4.12</td>
<td>3.93</td>
<td>4.00</td>
</tr>
<tr>
<td>8935</td>
<td>4.70</td>
<td>4.82</td>
<td>4.78</td>
<td>4.72</td>
<td>4.76</td>
</tr>
<tr>
<td>9097</td>
<td>4.98</td>
<td>5.05</td>
<td>4.90</td>
<td>4.80</td>
<td>4.93</td>
</tr>
<tr>
<td>9193</td>
<td>4.32</td>
<td>4.62</td>
<td>4.48</td>
<td>4.47</td>
<td>4.47</td>
</tr>
<tr>
<td>9447.5</td>
<td>6.09</td>
<td>6.23</td>
<td>6.20</td>
<td>6.22</td>
<td>6.18</td>
</tr>
</tbody>
</table>

5.2 Pressure Measurements

Using the methodology outlined in Chapter 4 for pressurized ultrasonic measurements, compressional and shear wave propagation at 0° and 90° (i.e. parallel and perpendicular to any textures such as, bedding, microfractures) were obtained.

Figure 5.3 and Figure 5.4 show an example of the compressional and shear wave propagations at different pressures for sample 7223.7 in Well 1. As it can been from the figures there are differences between the arrival times of the waveforms at 0° and 90°. The difference in compressional wave velocity between Vp0 and Vp90 is about 0.12 km/s, while a difference between Vs0 and Vs90 is about 0.6 km/s.
Figure 5.3 Example compressional wave propagation at varying pressures for sample 7223.7 for Well 1 at A) 0° and B) 90°. Each color denotes a different pressure step.
Figure 5.4 Example shear wave propagation at varying pressures for sample 7223.7 for Well 1 at A) 0° and B) 90°. Each color denotes a different pressure step.
Using travel time data obtained from graphs such as Figure 5.3 and Figure 5.4, velocities values were calculated for each pressure step. The values for each core at each pressure step are given in the appendix section under ultrasonic signals – pressurized measurements. Table 5.2 gives a summary of the Vp0 and Vp90 values for each sample at 1,000 psi during the pressure loading and unloading. Note that due to sample size constraints only Vp0 could be obtained for sample 7750.

Table 5.2 Summary of Vs0, Vp90, Vs0, Vs90 velocities obtained for core samples from Well 1. The velocities were obtained at a confining pressure of 1000 psi.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cycle</th>
<th>Vp0</th>
<th>Vp90</th>
<th>Vs0</th>
<th>Vs90</th>
<th>Vp0/Vs0</th>
<th>Vp90/Vs90</th>
</tr>
</thead>
<tbody>
<tr>
<td>7223.7</td>
<td>Loading</td>
<td>4.82</td>
<td>4.70</td>
<td>3.10</td>
<td>3.04</td>
<td>1.55</td>
<td>1.55</td>
</tr>
<tr>
<td>7223.7</td>
<td>Unloading</td>
<td>4.78</td>
<td>4.73</td>
<td>3.05</td>
<td>3.01</td>
<td>1.56</td>
<td>1.57</td>
</tr>
<tr>
<td>7228.2</td>
<td>Loading</td>
<td>4.81</td>
<td>4.01</td>
<td>3.03</td>
<td>2.56</td>
<td>1.59</td>
<td>1.56</td>
</tr>
<tr>
<td>7228.2</td>
<td>Unloading</td>
<td>4.83</td>
<td>4.17</td>
<td>3.02</td>
<td>2.61</td>
<td>1.60</td>
<td>1.60</td>
</tr>
<tr>
<td>7626.3</td>
<td>Loading</td>
<td>4.60</td>
<td>4.50</td>
<td>3.05</td>
<td>2.95</td>
<td>1.51</td>
<td>1.53</td>
</tr>
<tr>
<td>7626.3</td>
<td>Unloading</td>
<td>4.64</td>
<td>4.55</td>
<td>3.05</td>
<td>2.94</td>
<td>1.52</td>
<td>1.55</td>
</tr>
<tr>
<td>7750.7</td>
<td>Loading</td>
<td>4.14</td>
<td>NA</td>
<td>2.28</td>
<td>2.24</td>
<td>1.81</td>
<td>NA</td>
</tr>
<tr>
<td>7750.7</td>
<td>Unloading</td>
<td>4.11</td>
<td>NA</td>
<td>2.24</td>
<td>2.24</td>
<td>1.83</td>
<td>NA</td>
</tr>
<tr>
<td>7751.8</td>
<td>Loading</td>
<td>4.72</td>
<td>4.40</td>
<td>2.72</td>
<td>2.72</td>
<td>1.73</td>
<td>1.62</td>
</tr>
<tr>
<td>7751.8</td>
<td>Unloading</td>
<td>4.76</td>
<td>4.42</td>
<td>2.73</td>
<td>2.70</td>
<td>1.75</td>
<td>1.64</td>
</tr>
</tbody>
</table>

Figure 5.5 shows velocity-porosity trends for the compressional (Figure 5.5A) and shear (Figure 5.5B) velocities obtained for Well 1 and 1B (shear wave velocity for Well 1B is not used and the shear wave velocities were not clear). Figure 5.5A shows an inverse relationship between compressional velocity (A) and shear velocity (B) with porosity. Samples 7906, 7751.8, 9447.5, and 8539 lie outside the trend and will be discussed in Chapter 6 for potential effects of mineralogy in the Monterey formation. As mentioned in Chapter 3, the diagenesis of biogenic sediments, clays, and organic matter depend on the type of sediments present. These factors will be taken into account during the discussion session in Chapter 6.
Figure 5.5 Velocity porosity trends for data obtained from cores samples from Well 1 and 1B. A) Shows an inverse relationship between compressional velocity and porosity; however. B) Shear wave velocity was only obtained from samples from Well 1, an inverse relationship between shear wave velocity and porosity can still be observed.
In addition to mineralogy, fluid type, and saturation also affects velocity. Therefore, in order to estimate the change in velocity with fluid saturation, a fluid substitution was performed as described in Chapter 4.2.3. Figure 5.6 shows the changes the calculated compressional velocity of a rock that was mathematically saturated using brine with a salinity of 20,000 ppm. As compared to Figure 5.5A, the P-wave velocity increases after fluid substitution.

Note that Gassman’s relations have several assumptions and limitations, such as, low seismic frequencies, rock is isotropic, and all the minerals making up the rock have the same bulk and shear moduli. The Monterey formation does not fall under some these categories. For the rest of the thesis work we will use the velocity after fluid substitution. This is done recognizing the fact that the objective of modeling is not to give the absolute correct answer, but to give the most likely scenario. Figure 5.7 shows Vp0 and Vp90 as functions of the pressure loading cycle in a few core samples from Well 1. The data shows slight pressure dependence and the differences between the Vp0 and Vp90 values. These trends will be discussed and analyzed in Chapter 6.
Figure 5.7 Velocity-porosity trends for core samples from Well 1. For each one of the samples the velocities in the 0° and 90° directions are shown.
5.3 NMR Measurements

Results from low field NMR measurements from Well 1 and 1B are reported to understand the pore size distribution in rocks from the Monterey formation. The measurements were performed at dry and saturated conditions as described in Chapter 4. Additionally for each set of measurements (dry and saturated) an experiment was run on the same day of the measurements to record the background noise in the NMR instrument.

5.3.1 NMR Signals

Figure 5.8 shows the NMR signal obtained from core samples from Well 1 at different stages. In the first stage (Figure 5.8A) the NMR of dry samples was obtained. The main purpose for this stage was to determine if any bound water can be identified. Figure 5.8A shows that $T_2$ distributions for all samples lie between 0.01 and 1 msec and are centered at 0.1 msec.

In the second stage (Figure 5.8B), the NMR signal was obtained after the samples had been saturated with 20,000 ppm brine solution for 2 weeks. As compared to Figure 5.8A, Figure 5.8B shows that additional $T_2$ distributions between 1 to 1000 msec were obtained after saturation. Figure 5.8C shows the signals from the samples after correction for background noise. After the background correction was performed, the initial distribution centered on 0.1 msec was removed.

In Figure 5.8, the red line at 0.06 msec represents the minimum instrument time resolution. As it can also be observed from Figure 5.8A a significant portion of the raw signal obtained from the dry samples lies below the instrument resolution. However, once the sample has been saturated and, most importantly, after background correction has been performed (Figure 5.8C), the NMR $T_2$ distribution for the samples below the minimum 0.06 msec is ignored. This shows that most of the signal that was obtained for dry samples was due to noise in the system.
Figure 5.8 Figure shows NMR signals obtained from core samples from Well 1. A) NMR signals for dry samples. B) NMR signals from saturated samples. C) NMR signals from saturated samples after background correction. Red line at 0.06 msec represents the minimum instrument time resolution.
Figure 5.9 shows the NMR distribution for the same cores as in Figure 5.8, with the data shown in an incremental porosity scale as opposed to amplitude in uV units. The new scale was obtained by running an experiment on a known volume of bulk fluid (brine water). This allowed us to determine the amplitude of the signal from a known volume of water and to scale the signal from saturated samples to porosity units. The complete procedure is given in the appendix section under NMR porosity calculations.

![NMR Signals of Incremental Porosity against time](image)

**Figure 5.9** Well 1 NMR Signals of Incremental Porosity against time. Area under the curve represents porosity. A background correction has been done for each one of the curves. Red line at 0.06 msec represents the minimum instrument time resolution.

Figure 5.10 shows the NMR distributions of incremental porosity as a function of $T_2$ relaxation time for Well 1B. For these samples, the same procedures as in Well 1 were applied; only the saturated and background corrected signals are shown here. Figure 5.9 and Figure 5.10 will be analyzed further in the discussion section in Chapter 6.
Figure 5.10 Well 1B NMR Signals of Incremental Porosity against time. Area under the curve represents porosity. A background correction has been done for each one of the curves. Red line at 0.06 msec represents the minimum instrument time resolution.

5.3.2 NMR Porosity Calculations and Comparison

After obtaining the incremental porosity and $T_2$ relaxation time distributions, the area under the curve was calculated in order to get an estimation of the total porosity. Table 5.3 shows a summary of the calculated NMR porosities for different core samples from Well 1 as well as the density, the neutron, and the helium porosities. The table shows an overall good agreement with the porosity calculated by using helium porosimetry. However, when compared to density and neutron porosity the values are lower by a factor of two.
Table 5.3 Table shows the calculated porosity values from NMR T2 distributions for Well 1. Comparison against NMR porosity shows some agreement with the porosity obtained from Corelab (helium). However, porosity values from NMR are lower than the density porosity and neutron porosity values from well logs.

<table>
<thead>
<tr>
<th>Depth (ft)</th>
<th>Lab NMR Porosity (ml/ml)</th>
<th>Density Porosity (v/v)</th>
<th>Neutron Porosity (v/v)</th>
<th>Helium porosity (of cores from adjacent depths) (v/v)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5477.3</td>
<td>0.07</td>
<td>0.16</td>
<td>0.18</td>
<td>0.04</td>
</tr>
<tr>
<td>7220.8</td>
<td>0.06</td>
<td>0.11</td>
<td>0.19</td>
<td>0.05</td>
</tr>
<tr>
<td>7228.2</td>
<td>0.06</td>
<td>0.13</td>
<td>0.21</td>
<td>0.06</td>
</tr>
<tr>
<td>7750.7</td>
<td>0.08</td>
<td>0.07</td>
<td>0.15</td>
<td>0.05</td>
</tr>
<tr>
<td>7751.8</td>
<td>0.16</td>
<td>0.12</td>
<td>0.16</td>
<td>0.20</td>
</tr>
<tr>
<td>8154</td>
<td>0.04</td>
<td>0.13</td>
<td>0.19</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 5.4 Table shows the calculated porosity values from NMR T2 distributions for Well 1B. Comparison against NMR porosity shows that it is in good agreement with the porosity obtained from Corelab (helium). However, values deviate from those obtain by CMR tool and Density Porosity.

<table>
<thead>
<tr>
<th>Depth (ft)</th>
<th>Lab NMR Porosity (ml/ml)</th>
<th>Total CMR Porosity (cc/cc)</th>
<th>Density Porosity (v/v)</th>
<th>Neutron Porosity (v/v)</th>
<th>Helium porosity (v/v)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5360</td>
<td>0.11</td>
<td>0.09</td>
<td>0.15</td>
<td>0.21</td>
<td>0.11</td>
</tr>
<tr>
<td>5440</td>
<td>0.14</td>
<td>0.08</td>
<td>0.05</td>
<td>0.15</td>
<td>0.13</td>
</tr>
<tr>
<td>7906</td>
<td>0.06</td>
<td>0.09</td>
<td>0.09</td>
<td>0.15</td>
<td>0.06</td>
</tr>
<tr>
<td>8288</td>
<td>0.07</td>
<td>0.04</td>
<td>0.08</td>
<td>0.17</td>
<td>0.06</td>
</tr>
<tr>
<td>8333</td>
<td>0.01</td>
<td>0.04</td>
<td>0.09</td>
<td>0.14</td>
<td>0.02</td>
</tr>
<tr>
<td>8539</td>
<td>0.02</td>
<td>0.06</td>
<td>0.00</td>
<td>0.11</td>
<td>0.02</td>
</tr>
<tr>
<td>8632</td>
<td>0.03</td>
<td>0.03</td>
<td>0.09</td>
<td>0.25</td>
<td>0.02</td>
</tr>
<tr>
<td>8935</td>
<td>0.02</td>
<td>0.03</td>
<td>0.08</td>
<td>0.15</td>
<td>0.01</td>
</tr>
<tr>
<td>9097</td>
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<td>0.03</td>
<td>0.09</td>
<td>0.13</td>
<td>0.01</td>
</tr>
<tr>
<td>9193</td>
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<td>0.02</td>
<td>0.00</td>
<td>0.08</td>
<td>0.02</td>
</tr>
<tr>
<td>9447.5</td>
<td>0.02</td>
<td>0.07</td>
<td>0.00</td>
<td>0.13</td>
<td>0.01</td>
</tr>
</tbody>
</table>
6. DISCUSSION

6.1 Ultrasonic Measurements

Very few studies exist about the velocity variations in biogenic silicate reservoirs, such as the Monterey Formation. However, Chaika (1998) obtained ultrasonic measurements from sample in the Monterey Formation from three different wells in three different fields in the San Joaquin Basin. The fields are Cymric, McKittrick, and Asphalto. The core samples from the Cymric field extend from 1241’ to 1259’ and consist mainly of Opal-A and Opal-CT (with minor amounts of quartz 2% for one sample). The data from McKittrick field extends from 3248.5’ to 3684.5’ - those samples are mainly composed of Opal-CT (65 to 97% by weight). The Asphalto has core data available from 5875’ to 5958’ and it is composed mainly of quartz (36 to 70% by weight) (with the exception of one core sample at 5937’ which is composed of 46% Opal-CT by weight).

Figure 6.1 shows that my study area lies in the proximity of the Midway-Sunset field and along the depositional trend of Chaika’s (1998) data. Thus, the Opal data from Chaika (1998) can be extended with the porcelainite and quartz data obtained in this study. Figure 6.2 shows the compressional velocity – porosity trends from core samples from Wells 1 and 1B. As it can be observed from Figure 6.2 there is a tight inverse velocity - porosity correlation with a few exceptions.

Chaika (1998) data shows the extension of the correlation to high porosity regions. As it can be observed from the figures some samples (7906, 7751.8, 8539, and 9447.5) deviate from the main velocity - porosity trend. The three latter samples have higher velocity values, while sample 7906 has lower velocity values than the main trend. In the following section, I will analyze the reasons for this velocity variation. In order to provide the best representation for reservoir conditions the P-wave velocities plotted on the following figures were obtained after a fluid substitution computation.
Figure 6.1 Map shows oil fields in the San Joaquin Basin. A red star represents the Cymric, McKittrick, and Asphalto fields which were analyzed by Chaika (1998). The red arrow represents the differences in diagenetic stage from the data obtained by Chaika (1998), starting with Opal-A processing to Opal-CT and later on to quartz. On the same graph the area of this study in highlighted by a dark brown rectangle. This area lies along the Midway-Sunset (MS) field.
Figure 6.2 Compressional Velocity-porosity trends for data obtained from Well 1 and Well 1b along with data collected by Chaika (1998) for Opal-A, Opal-CT, and quartz phase from the San Joaquin Basin. A) Velocity from dry rock samples, B) Velocity after fluid substitution.
Fluid substitution was performed on compressional data collected in this experiment and also that by Chaika (1998). There are limitation and assumptions that need to be taken by using this approach. However, I recognize the fact that both rock and fluid properties affect ultrasonic velocity and in order to have a closer approximation to the conditions in the well the velocities must be saturated. Figure 6.3 shows that greatest increases in velocity were observed for the Opal-A and Opal-CT samples. This is expected as these samples have higher porosity values than the rest. The lowest change in velocity occurred for samples 8539 and 9447.5 which have a high dolomite content and low porosity values.

Figure 6.3 Saturated compressional velocity (after fluid substitution) and dry compressional velocity for samples from Well 1, 1B, and that collected by Chaika (1998). Blue line makes line of equality.
The XRD data (Table 4.2) provides an explanation for the deviation from the velocity - porosity trend for some of the samples in Figure 6.1. For example, Sample 7906 is mainly composed of quartz (59.2% by weight), however significant amounts of calcite (15.5%), and clay (11.1%). Han et al. (1986) have shown that velocity values can be reduced significantly with the addition of clay. Table 2 also shows that samples 8539 and 9447.5 mainly consist of dolomite. This explains their higher velocity values. Although, Sample 7751.8 does not have XRD data but Table 4.3 shows its grain density value to be about 2.75 g/cm³. Since this value is very close to the density of limestone (2.71 g/cc), an acid test was performed on a piece of this sample: Since no effervescence with HCl was observed, the sample might be a mixture of dolomite and quartz. This will explain why compressional velocity is higher than the trend established by using the rest of the data. Figure 6.4 the shear velocity – porosity trends from the core samples from Well 1 along with the data collected by Chaika (1998). The figure shows an inverse relationship between shear velocity and porosity.

**Figure 6.4** Shear Velocity-porosity trends for data obtained from Well 1 along with data collected by Chaika (1998) for Opal-A, Opal-CT, and quartz phase rocks of the Monterey from the San Joaquin Basin.

Given the correlation between velocity and porosity, we investigate probable causes of porosity reduction and possible spatial distributions of porosity. Figure 6.5 shows the structure
of the south-west section of the Monterey formation. The thickness of the Monterey formation (Figure 6.5A) and the elevation of the top of the Monterey composite surface (Figure 6.5C) both increase towards the South. An overall trend of deepening can be observed and this implies that Monterey Formation in our area of study have under higher overburden stresses. Therefore, it can expected that rocks from this section would have lower porosity values. An important point to note is that a series of mountain ranges are encountered towards the West. For this area of study, the Temblor range would be encountered implying that sections of the Monterey might have been uplifted by the effect of tectonic movement.

Figure 6.5  A) Map showing the estimated variation in the estimated thickness of the Monterey formation. B) Elevation of Monterey Composite Surface (feet). C) Structure map of the Monterey Composite Surface. Area closed in the rectangle shows current area of study and red line shows section studied by Chaika (1998) (modified from Scheirer, H.A., 2003).
An important point to keep in mind is that as mentioned in Chapter 2, lower sections of the Monterey formation have generally higher calcareous (warmer climate during that time period) content (Graham and Williams, 1985). Previous studies have concentrated on shallower sections of the Monterey formation which are mainly composed of biogenic sediments however, since our cores lie on a deeper section we will see the influence more carbonate rich deposits.

Figure 6.6 shows the compressional velocity - porosity trends for Well 1, along with the data from this study and from Chaika (1998). Notice the separation between the data obtained in the laboratory and that from logs at porosity values lower than 20%. It is important to mention that the porosity used for the well log data is neutron porosity, while that used for the laboratory is helium porosity. For the core samples used in this study most the data points lie outside of the trend given by log data (only exception is sample 7751.8 which lies inside the zone), whereas the majority of the data obtained by Chaika (1998) lies inside the trend given by the log data. Since He-porosity values are lower than neutron porosity, the data would match by matching the laboratory measured and the well log porosity data, as shown in Figure 6.6. There are two possible explanations for the porosity mismatch. (1) Clay minerals: the porosity measurements do not capture porosity still trapped as clay bound water. (2) Fractures: core plugs do not capture fracture porosity due to sampling.

Figure 6.7 shows the compressional velocity – porosity trends for Well 1 and the velocity data collected for Wells 1 and 1a. In this graph, NPHI was used for the log and the core data. As seen in the figure, when using NPHI porosity only two data points which correspond to samples with a high (80%) dolomite content by weight fall outside of the trend. The rest of the data points fall within the well log data. It is apparent from Figure 6.7 that most of the data collected by Chaika (1998) lies above 6,000 ft. Since the reservoir interval lies below 6,000 ft, from this point forward, the analysis will be limited to data from zones below 6,000 ft.
Figure 6.6  Compressional Velocity - Porosity trends for Well 1. Neutron porosity (NPHI) is used for the well log data, whereas helium porosity is used for the laboratory data (Well 1, Well 1b, and Chaika (1998). Notice the separation between the data obtained from the laboratory and that from logs. (Color bar represents depth (ft).)
Identification of pay zones with conventional methods, such as high resistivity in hydrocarbon-bearing zones, is a major problem in exploration of the middle and lower sections of the Monterey formation. Zones with high resistivity values have been found to produce mainly water, while zones with low resistivity have been found to produce profitable amounts of oil (personal information Chris Peltonen, Venoco). Figure 6.8 shows velocity-porosity trends for Well 1 (Figure 6.8A) and Well 2 (Figure 6.8B) color-coded by resistivity from logs.
Figure 6.8 Compressional Velocity - Porosity trends for Well 1 below 6000 ft. Neutron porosity (NPHI) is used for the well log data as well as for Well 1 and Well 1b lab data. Helium porosity is used for the data from Chaika (1998). (Color bar represents log of resistivity (ohm)). Notice the differences in resistivity between Well 1 (A) and Well 2 (B).
A comparison between the two wells shows that Well 1 has relatively higher resistivity values than Well 2, for porosity below 20%.

Keeping in mind that NPHI overestimates the porosity values for deeper zones (Figure 6.6 and Figure 6.7) and unexpected behavior of the resistivity curve, the next step was to analyze the log data for any indication of the presence of clay. Shows spectral gamma ray, total gamma ray, and resistivity logs for well 1, 1B, and 2 (Figure 6.9) show that for the depths (greater than 6,000 ft) being analyzed in this study thorium levels increase. Thorium is represented by the purple curve on the spectral gamma ray track. Zones with high concentration of thorium (higher than 4 ppm) are highlighted by red rectangles. Additionally, these zones with high thorium also have a decrease in resistivity.

Figure 6.9 Spectral Gamma (track 1), Total Gamma Ray (track 2), and Resistivity (track 3) logs for Wells 1, 1B, and 2. Zones highlighted by the red rectangles are high thorium zones (purple color section on spectral gamma ray track).
Figure 6.9 also shows a difference in thorium concentration between Well 1 and Well 2. In Well 1, about one third of the data (approximately 1,200 ft out of 3,500 ft) have thorium concentrations higher than 4 ppm, while in Well 2 about two thirds of the data (about 2100 ft out of 3,000 ft) have thorium contents higher than 4 ppm (Figure 6.10). In Well 1 (Figure 6.10A) most of the data have thorium content under 5 ppm while Well 2 (Figure 6.10B) shows some zones with thorium content as high as 10 – 15 ppm.

Figure 6.10 Compressional Velocity - Porosity trends for Well 1 (A) and Well 2 (B). NPHI is used for log and lab data.). (Color bar: thorium content in ppm). Labels point is oil/water ratios obtained from Dean Stark experiment.
Figure 6.11 shows thorium and potassium cross plots with deep resistivity as color scale for well 1 (Figure 6.11A) and well 2 (Figure 6.11B). Figure 6.11 shows that an increase in thorium and potassium content is marked by a decrease in the recorded resistivity values. In general, Well 2 appears to have higher thorium than Well 1.

Figure 6.11 Thorium and potassium crossplots for well 1 (A) and well 2 (B). Color scale is log of deep resistivity in ohm-m from log data. Graph shows a decrease in resistivity with an increase in thorium and potassium content.
Hassan et al. (1976) have associated the increase in thorium values with increased input of terrigenous clays. Additionally, Bohacs and Schwalbach (1994) reported that for the Monterey formation in Napes Beach California, high levels of thorium occur coincident with volcanic ash beds, while potassium correlates with aluminum which is used as a predictor of detritus content. Therefore, the increases in potassium and thorium content observed in the lower section of the Monterey can be attributed to increases of input in terrigenous clays and volcanic ash. This would explain the increase in the NPHI readings and the decrease in the resistivity values. The bound water in the clays would increase the NPHI readings (higher hydrogen content), and reduce the resistivity readings.

Only Well 2 had an elemental capture spectroscopy (ECS) log which allows us to investigate the distribution of different rock minerals throughout the well. Figure 6.12 shows compressional-velocity trends for well 2 and clay content from an ECS log as color scale. Figure 6.12 shows increases in clay content with increasing depth (represented by red arrow). It also important to note the similarities between Figure 6.12 and Figure 6.10B which shows an increase in thorium content with increasing depth.

Figure 6.12 Compressional velocity - porosity trends for Well 2. NPHI is used well log data as well as for lab data. Helium porosity is used for data from Chaika (1998). (Color bar: clay content from elemental capture spectroscopy log (ECS) in decimal percent). Labels for each data point are oil/water ratios from Dean Stark experiment.
The differences between lab porosity and NPHI as well as the irregular behavior of the resistivity curve have been linked to an increase in the clay content for the lower section of the Monterey formation. However, this factor does not fully explain the trends seen in velocity-porosity data from the laboratory and the variation in o/w ratios. This question can be addressed by analyzing the distribution of other minerals for Well 2. As shown earlier, data from samples with significant amount of dolomite fell outside the trend of silica diagenesis. This was the first indication that dolomite could affect the properties of rocks in the lower section of the Monterey.

Figure 6.13 shows the compressional velocity – porosity trends for well 2 with carbonate content from ECS log as color scale. The figures show an increasing amount of carbonate with increasing depth (mark by red arrow). Most importantly, the amount of carbonate for samples 8539 and 9447.5 (label as 0.57 and 0.38 o/w ratio respectively) fall on the scatter of data points that have highest carbonate content, which matches the XRD data provided in Table 4.4. Additionally, it should also be pointed out that a trend with o/w ratio can be observed.

The cores with carbonate content higher than .35% have o/w ratios higher than 35%. The only exception is core 7906 which is labeled as having an o/w ratio of 51% and falls outside of the zones with high carbonate content. However, as shown Table 4.4 this core is composed of 59.2% quartz, 15.5% calcite, and 4% dolomite by weight. Therefore carbonate minerals still make up a significant amount of the core. Those cores with 0 o/w ratio signify that no dean stark experiment was performed in the core.

Overall, these trends show that carbonate material can help in the transportation and storage of oil in the Monterey rocks. The wettability and the pore space can be attributed to these observations. This brings a new perspective where flow or transportation is not only attributed to fractures in the Monterey rocks.
Figure 6.13 Compressional velocity – porosity trends for Well 2. NPHI is used for the well log data as well as for lab data. Helium porosity is used for data from Chaika (1998). (Color bar: carbonate content from elemental capture spectroscopy (ECS) log in decimal percent). Labels for each data point are oil/water ratios obtained from Dean Stark experiment. Zero denotes no data available.

Figure 6.14 shows the compressional velocity – porosity trends for well 2 with quartz and feldspar content from ECS log as color scale. The figures show a decreasing amount of quartz and feldspar with increasing depth (represented by red arrow). Most importantly, it shows the sample that lies in the zone with the highest (80% and higher) quartz and feldspar content also has the lowest o/w ratio.
Figure 6.14 Compressional Velocity - Porosity trends for Well 1. Neutron porosity (NPHI) is used for the well log data as well as for Well 1 and Well 1b lab data. (Color bar represents quartz and feldspar content from elemental capture spectroscopy log (ECS) in decimal percent). Values for each data point are oil/water ratios obtained from Dean Stark experiment. Zero denotes no data available.

In summary, our velocity, porosity, and resistivity analysis shows that high clay content in the lower section of the Monterey formation increases the NPHI and reduces the resistivity readings from logs. Additionally, higher carbonate (dolomite) content leads to velocities that are higher than those with only silica; high carbonate content is also correlated with o/w ratios higher than 35%. These results are unique to the lower section of the Monterey formation due
to higher calcareous deposition in the warmer climate prevalent during that time period (Graham and Williams, 1985).

### 6.2 Pressurized Ultrasonic Measurements

Figure 6.15 shows the compressional velocity – pressure trends for core samples from the Monterey formation. The Opal-A, Opal-CT, and quartz data from Chaika (1998) show definite trend of increasing compressional velocity with decreasing porosity. The lowest porosity value analyzed by Chaika (1998) was 14.9% belonging to a core mainly composed of quartz. In this study, velocity – pressure data was obtained for core samples with porosities ranging from 2.8 to 20 %. The highest pressure was calculated by integrating the density log. The velocity values plotted in Figure 6.15 are the Vp0 and Vp90 for each core. The data obtained in this study does not show a definite trend of increasing compressional velocity with decreasing porosity. For example sample 7751.8 has a helium porosity of about 20% yet, plots along the same trend as sample 7626.3 which has a porosity value of 3.2%. Also sample 7750.7 has a porosity of 6% yet it has velocity values lower than sample 7228.2 which has porosity of 4.5%. An explanation for this behavior can be provided from the results obtained from the previous section (discussion of ultrasonic measurements at benchtop conditions). One of the main results from the previous section was that the presence of carbonate content affects the velocity values. Cores with higher dolomite content have higher velocity values and therefore do not follow the trend established for rocks that have mainly of biogenic silicate (i.e. Opal-A, Opal-CT, quartz) material. If data from samples 7751.8 and 7751.7 were removed from the rest of the cores (7228.2, 7626.3, and 7223.7) would show the trend of increasing velocity with decreasing porosity. Additionally the samples have higher velocity values than those studied by Chaika (1998), which is expected as they have significantly lower porosity values.

The rocks show minimal pressure dependence. This shows that biogenic quartz has a different behavior than clastic quartz which commonly has strong pressure dependence (Han et al. 1986).
Figure 6.15 Compressional velocity-pressure trends for core samples from the Monterey formation. Opal-A, Opal-CT, and Quartz data was obtained from Chaika (1998). The data for obtained from this experiment is given along with its respective porosity value.

Figure 6.16 shows shear velocity – pressure trends for core samples from the formation. This plot also shows a trend of increasing velocity with decreasing porosity. As seen in Figure 6.16 the shear velocity collected for this experiment shows that samples 7751.8 and 7750.7 also does not follow the main trend. For example, sample 7751.8 with high dolomite content plots in the same range as sample 7228.2, which has a lower porosity. Figure 6.17 shows a summary of the velocity-pressure trends and the areas in which each of the lithologies lie.
Figure 6.16 Shear velocity-pressure trends for core samples from the Monterey formation. Opal-A, Opal-CT, and Quartz data was obtained from Chaika (1998). The data for this experiment is given along with its respective porosity value.
Figure 6.17 Velocity-porosity trends can be used to identify lithologies. Porcelanites lie in porosities higher than 0.2 and carbonate rich samples have higher velocities.
6.3 NMR Measurements

The next step in the analysis is to study the pore size distribution and porosity by using NMR signals and to find a relationship between the ultrasonic measurements and those the NMR analyzes.

The NMR \( T_2 \) distributions obtained from cores were sorted based on two main factors, namely mineralogy and shape of the NMR \( T_2 \) distributions. Since mineralogy data were not available for all cores similarity in the shape of the \( T_2 \) distribution was used. The main idea was correlate NMR data in samples without XRD data, with those that have similar NMR \( T_2 \) distributions along with XRD data.

In the previous section it was shown that mineralogy was the main factor affecting velocity data. Three groups where identified: quartz dominated; carbonate/dolomite dominated; and significant amount of clay content. These groups will be analyzed in this section.

Quartz Dominated

Figure 6.18 shows the incremental porosity – \( T_2 \) relaxation time distribution obtained from core samples from Well 1 and 1B. The core samples have similar shape distribution XRD data for samples 7220.8 and 8154.5 show that they have quartz content higher than 65% (by weight). XRD data from samples 8333, 8935, 9097, and 9193 show that they have a quartz content higher than 71%. However, sample 8333 does not quite follow the same trend, possibly due to low signal to noise ratio (Table B.1). Sample 8333 has a signal to noise ratio lower than 75.

Sample 54773.3 does not have XRD data available as mentioned earlier however, by the shape of the distribution it can be speculated that its bulk mineralogy is mainly composed of quartz. The differences in the distribution and average time values can be explained by the fact that core 5477.3 lies in a shallower section and therefore bigger sizes as they have not been compacted to the same extent as the rest of the samples. Another explanation is that as mentioned in Chapter 2, shallower depths of the Monterey formation correspond to a time of
basin filling (Graham and Williams, 1985) which means more clastic input can be expected. Therefore, the differences in incremental porosity distributions can also be attributed to differences between clastic quartz and biogenic quartz. The latter having significant amount of its porosity the micro range.

Figure 6.18 Incremental porosity – time distributions obtained from NMR experiment for core samples from Well 1. The core samples presented in this graph have similar shape. Sample 8154.5 has been crossed out as it had a signal to noise ratio lower than 75. Red line at 0.06 msec represents the minimum instrument time resolution. The black dash line presents the average of the two modes for samples 7220.8 and 7228.2. The blue dash line presents the average of the distribution.

Figure 6.19 shows the incremental porosity – time distribution obtained from NMR experiment obtained from core samples from Well 1 and 1B. XRD is not available for samples
7750.8 and 7751.8; earlier analysis showed that these samples are mainly composed carbonate material. A small amount HCl acid was placed on the cores no reaction was observed, therefore it was concluded that the mineral is most likely dolomite. Figure 6.19 also shows a distribution between the two samples for samples 7750.8 and 7751.8. A multimodal distribution in T2 relax time is observed in these samples. Since these samples are predominantly carbonates, the distributions could be due to variations in pore sizes or by mixed mineralogy. Samples 8539 and 9474.5 are from well 1B and they have a dolomite content higher than 80%. The analysis shows that dolomite is the common mineral between all of the samples mentioned. An important fact to mention is that the ultrasonic analysis showed that these samples did not follow the trend of silica diagenesis for the Monterey and also had the highest oil/water rations a mixed mineralogy was also assessed during the velocity analysis as shown in Figure 6.13 and Figure 6.14.

![Graph showing incremental porosity vs. time for core samples from Well 1. Red line at 0.06 msec represents the minimum instrument time resolution.](image-url)

Figure 6.19 Incremental porosity – time distributions obtained from NMR experiment for core samples from Well 1. Red line at 0.06 msec represents the minimum instrument time resolution.
Core samples from well 1B have the benefit of having available XRD data. Therefore, incremental porosity – time distributions obtained from NMR were grouped mainly on their mineralogy. This will help answer some of the questions of rock composition from core samples from well 1 that do not have XRD data available.

Mixed Mineralogy

Figure 6.20 shows the incremental porosity – time distribution from NMR for core samples from Well 1B. The samples plotted on the figure are 5360, 5440, and 7906. Sample 5360 is has a bulk mineralogy composed of 83.6% quartz, 2.8% calcite, 1.5% dolomite, and 7.3% clay. The sample has bimodal distribution with the first mode having an average of 15 msec and the second of mode of 180 msec.

The distribution has a very similar shape to that of sample 5477.3 from well 1. Additionally, the average for the first mode is the same for both samples (15 msec). Therefore it can concluded that sample 5447.3 is also mainly composed of quartz.

Sample 5540 is composed of 55.2% quartz, 38.5% dolomite, and 4.9% clay. This sample shows a bimodal distribution with the first mode having an average of 2 msec and the second 30 msec. This is very similar to the signal obtained from sample 7750.8 and the first two nodes of sample 7751.8 (Figure 6.19). Both samples 7750.8 and 7751.8 were speculated to be composed of quartz and dolomite.

All three samples lie in the same area on the compressional velocity – porosity plots (Figure 6.13 and Figure 6.14). Sample 7906 is composed of 59.2% quartz, 15.5% calcite, and 11.1% clay. However, this sample had a poor signal to noise ratio (lower than 72), and therefore the data could not be fully trusted.

Appendix B contains information regarding the experimental setup and background correction for the NMR experiments. Additionally, this section also contains the signal to noise ratios for the rest of the core samples.
Figure 6.20 Incremental porosity – time distributions obtained from NMR experiment for core samples from Well 1B. Red line at 0.06 msec represents the minimum instrument time resolution. Sample 7906 has been crossed out as it had a signal to noise ratio lower than 75. XRD data for this samples show quartz content higher than 55%.

High Clay Content

Figure 6.21 shows the incremental porosity – time distribution from NMR for core samples from Well 1B. The samples plotted are 8288 and 8632. Both these samples have clay content higher than 20%. The bulk mineralogy of sample 8288 is composed of 41.8% total clay, 39% quartz, 5.9% feldspar, and 2.9% dolomite. This sample shows a bimodal distribution with the first mode having an average of .4 msec, while the second has an average of 150 msec. The first mode is attributed to the presence of clays while the second to quartz and feldspar. Sample 8632 is composed of 50.4% quartz, 24.2% clays, and 6.9% calcite. This sample has a
trimodal distribution with the first mode having an average of 0.4 msec (same as first mode for sample 8288); second mode has an average of 5.5 msec, and the third 550 msec. The first mode is attributed to the presence of clays as it has the same average value as sample 8288. The second and third modes are attributed to the presence of calcite and quartz.

Figure 6.21 Incremental porosity – time distributions obtained from NMR experiment for core samples from Well 1B. XRD data for these samples shows total clay content higher than 20%. Red line at 0.06 msec represents the minimum instrument time resolution. Black dash line shows similarities between both samples for the first mode. Blue line represents the average time value for the second mode in core 8288.

Figure 6.22 shows the velocity porosity trends and its relationship to NMR $T_2$ distributions. As it can be seen from the figure, areas that had been identified as a specific lithology also have similar $T_2$ distributions.
One of the key points for this study was to investigate the differences between biogenic quartz and clastic quartz. Figure 6.23 shows the difference in distribution between a Berea sandstone core and samples 5360 and 8935 from well 1 which are mainly composed of quartz and come from different depths.

Figure 6.23 illustrates that although all three samples have relaxations peaks around 100 msec indicating large pore sizes, only the Berea sandstone has the maximum T$_2$ distribution amplitude in this section. Core samples 5360 and 8935 have maximum T$_2$ relaxations at lower times (15 and 0.5 msec, respectively), indicating presence of significant amount of small pores in the biogenic quartz.
6.4 NMR and Mercury Injection Relationship

As mentioned earlier the distributions of NMR relaxation data can be affected by the parameters used to performed the experiment and the mathematical inversion used on the amplitude data (conversion from amplitude to $T_2$). In order to obtain reliable pore size distributions from $T_2$ relaxation times, we compared our results with mercury injection results on selected samples. The mercury injection experiments for samples 5477.1 and 7751.8 were performed by an outside vendor, while for the rest of the samples (7228.2, 7750.8, 8935, 9193, 8539, and 8632) by Benjamin Harrell from PTS laboratories Inc.
This analysis is based on the principle that in a water-wet, fully water-saturated rock, the $T_2$ relaxation time of a single pore is proportional to the surface area to volume ratio of that pore, which in turn is a measure of the size of the pore (Coates et al. 1999). Thus, PSD from NMR data can be compared to the pore throat size distribution obtained from mercury injection data. However, in order to compare the data, the pore radius data obtained from mercury injection is converted to an equivalent T2 value. According to:

$$T_2 = \frac{1000r}{2\rho_e} \quad \text{(Marshall et al., 1995)}$$

Where $T_2$ is in msec, $r$ is the pore radius obtained from mercury injection in µm, and $\rho_e$ is the effective surface relaxivity in µm/sec.

Coates et al. (1999) noted that the effective surface relaxivity term is introduced to account for the fact that NMR responds to pore body size whereas mercury injection capillary pressure is controlled by pore throat sizes. The $\rho_e$ is proportional to the product of intrinsic surface relaxivity and ratio of pore throat size to pore body size.

Figure 6.24 shows the relationship between mercury-injection pore size distribution and $T_2$ distribution for sample 7751.8 from well 1. Note that the mercury injection data matches NMR data for a $\rho_e$ of 6 um/sec. This value is in accordance to values reported by Coates et al. (1999) who obtained a value of 5.35 um/sec for a dolomitic rock. However, sample 8539 which was mainly composed of dolomite, obtained a value of 1 um/sec.

The values obtained and those published by Coates et al. (1999) show that a correlation between pore body to pore throat ratios can be established for rock samples. Additionally, it also establishes that the effective relaxivity can be determined by matching the NMR $T_2$ and mercury injection capillary pressure data.
6.4.1 Well 1 - Quartz Dominated

Figure 6.25 and Figure 6.26 shows the match between mercury injection pore size distribution and $T_2$ distribution for samples 5477.1 and 7228.2 from well 1. Both samples are quartz dominated. The $\rho_e$ values used were 1 and 2 um/sec respectively. This is significantly lower than the values reported by Coates et al. (1999) who published a value of 23 um/sec for sandstone. However, the difference between the numbers can be explained by the fact that rocks in the Monterey formation with high quartz content are not well represented by sandstones. Quartz rich rocks in the Monterey formation are marked by a considerable amount of small pore sizes, therefore the $\rho_e$ would also be small.
Figure 6.25 Relationship between mercury-injection pore size distribution and $T_2$ distribution for sample 5477.1 from well 1. The original mercury injection data was translated by using a $\rho_e$ of 1 um/sec.

Figure 6.26 Relationship between mercury-injection pore size distribution and $T_2$ distribution for sample 7228.2 from well 1. The original mercury injection data was translated by using a $\rho_e$ of 2 um/sec.
The NMR and MICP comparison for all samples can be found in the appendix section of this document. Table 6.1 provides the summary of the parameters found through the analysis and comparison between mercury injection porosity and NMR porosity. For the most part, NMR porosity is higher than mercury injection porosity. The difference between the readings might be due to the fact that only 2 grams were used for mercury injection measurements whereas the whole core was analyzed in NMR measurements. Also, the NMR measurements are not dependent on the fluid being able to imbibe the pore space and it can also take into account the bound water already existent in the core.

Table 6.1 Effective surface relaxitivity found for cores from well 1 and mercury injection porosity.

<table>
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<th>Core</th>
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<td>2.8</td>
</tr>
<tr>
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<td>8935</td>
<td>2</td>
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<tr>
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<td>9193</td>
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<td>0.7</td>
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</table>

Finally, using an average $\rho_e$ value of 1.84 um/sec and commercial software TECHLOG (2011.1), the T2 distribution from the CMR log in well 1B was converted into capillary pressure (Figure 6.27). As it can be observed from the figure the zones with low capillary pressure are accompanied with high oil and/or gas shows from mud log.
Figure 6.27  Well log template for well 1B. Track 1 shows spectral gamma ray, track 2 total gamma ray, track 3 resistivity, track 4 oil (green) and gas (red) shows from mud log, and track 5 calculated capillary pressures from CMR log. In all tracks values increase to the right.
7. CONCLUSIONS AND FUTURE WORK

The laboratory and well log analysis made in this thesis have shown that mineralogical differences can be distinguished. The mineralogical differences can explain variations in saturations. Specifically,

- At the same porosity, rocks with considerable amount of carbonate or dolomite content have higher compressional wave velocity.
- Pore size distributions in rocks with considerable amount of carbonate or dolomite content are distinct from siliceous rocks.
- The carbonate-rich zones correlate well with oil/water ratios higher than 0.35.
- There is major difference between biogenic siliceous and clastic rocks: small, micron-sized pores make up a considerable amount of porosity in the biogenic quartz phase.
- Mercury injection and NMR studies show that a value of 6 um/sec and about 1 um/sec can be used for surface relaxivity ($\rho_e$).

The velocity – porosity trend in biogenic siliceous rocks is distinct. Silica phase change leads to porosity loss and velocity increase that is not seen in detrital silicate.

- The velocity – porosity trend in biogenic siliceous rocks is higher than in detrital silicates
- As opposed to detrital silicate rocks, velocity has only small pressure dependence and velocity anisotropy is prevalent in layered samples.

The lower section of the Monterey formation (McDonald and Devilwater) is unique and different from the upper sections. Specifically, the McDonald and Devilwater zones have:

- Marked increase in detrital clay content that can be distinguished by high thorium content on spectral gamma ray logs. Due to the high clay content, neutron porosity is high and resistivity values are low on well logs.
- Increasing amounts of carbonate content that increases the density and velocity of rocks.
8. FUTURE WORK

Since the silica-rich lithologies are distinct from carbonate-rich zones, it is important to understand their effect on our measurements. This study was made on dry cores. The samples are prepared and ready for saturated measurements. It will be important to perform the velocity experiments under saturation to understand the effect of fluids (brine and oil) on siliceous and carbonate rocks. Some samples have been prepared for complex resistivity studies. It will be important to perform these experiments to identify and quantify the changes in resistivity between the rocks. The difference in NMR response due to the effect of fluids on silica rich and carbonate rich samples need to be investigated. This type of study will yield information about possible preferential imbibition of oil in certain minerals. Additionally, a systematic study of NMR and capillary measurements is needed to quantify the effects of mineralogy and pore structure.
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APPENDIX A. ULTRASONIC MEASUREMENTS
Chapter 2 presents the results of ultrasonic velocity measurements at benchtop and pressurized conditions. This appendix presents the core sample assembly, sample saturation procedures, and raw ultrasonic signals (benchtop and pressurized).

A.1 Core Assembly
As discussed earlier the samples have been prepared for ultrasonic as well as complex resistivity measurements at different angles. The original idea for this type of measurements came from William Woodruff. I would like to thank him in this section for this teaching and support through the assembly of the cores.

The workflow of the sample preparation is as follows:

a. The initial step is to make sure that all cores are made flat on the surfaces ends. This step is especially important as rubber gasket and end cap will be placed on the ends.
b. Measure core length in at least 4 different directions.
c. Drill electrodes holes by using one of the methods used by surface electrical resistivity surveying. For this experiment it was decided to use the Wenner array. This means that the distance between each one of the electrodes.
d. The diameter and depth of the hole depends on the size of the silver electrode. For this study a 1 mm diameter by 2.5 mm length electrode from invivo metric was used. The electrode is attached to a 70 mm silver wire. Refer to Figure A.1.

e. Identify the directions of minimum and maximum velocity using panametric transducers at different directions. Refer to Figure A.2.

Figure A.1 Silver electrode and wire used for study.
Table 1: Compressional Velocity Measurements

<table>
<thead>
<tr>
<th>Direction Angle (degrees)</th>
<th>Compressional Velocity (km/s)</th>
</tr>
</thead>
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<tr>
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<tr>
<td>90</td>
<td>5.102</td>
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<td>135</td>
<td>5.019</td>
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</tbody>
</table>

Figure A.2 Compressional Velocity was measured at different angles in the core using panametric transducers in order to determine the directions of maximum and minimum velocities.

f. After determining the directions for maximum and minimum velocity the surfaces of the cores are made flat. As it can be seen on Figure A.3 the flat areas lie in between the holes for the electrodes. These flat areas are needed in order to have a good connection between the ultrasonic crystals and the core.

g. Record the distance between each one of the flat areas. Make sure to take several measurements as this distance will be needed for the calculation of velocity (etc. distance the wave travels across the cores).

Figure A.3 Core sample after electrode holes have been drilled surfaces have been made flat for ultrasonic crystals.
h. The next step is to prepare the P- and S-wave crystals. For this experiment the crystals were obtained from Piezo-Optics and they have a frequency range of 50 KHz to 100 MHz (+/- 5%). There are several options on the crystals but for this experiment it was decided to use the solid on both sides option and to cut them down to the needed dimensions. As it can be seen on Figure A.4 the crystals are circular shape and they have a diameter of about 1 in. Four rectangular pieces (.25 x .2 in) were cut from one crystal.

![Figure A.4 Transducers crystals used for measurements and schematic of cuts made on crystal.](image)

i. Each one of the rectangular crystal pieces has to be prepared. The first step is to cover only the sides of the crystal where the piezoceramic (quartz) is exposed. The ends of an insulated wire are clean one is glued to the surface of the crystal by using silver conducting epoxy. Once the conducting epoxy is dried 5 min epoxy is added on top. The final step is to put a layer of nail polish on all the surfaces except for the bottom of crystal as this will be attached to the core. The nail polish is used as an electrical insulator. Refer to Figure A.5.
Figure A.5 A) Schematic representation of P- and S-wave crystal preparation. Conducting epoxy is used in one of the surfaces to connect an insulated cable to the surface; this is then covered with 5 min epoxy. The final step is to cover all surfaces except for bottom with nail polish which will act as electrical insulator. B) Example of final prepared ultrasonic crystal.

j. Next the crystals are placed on the core on their respective places. The first step is to mix the silver conducting epoxy and spread it on the flat areas and in between them. This is done to create a connecting between all of them. Second place each one of the crystals carefully. Make sure to press on them, in order to get rid of any air bubbles. Use a rubber band to hold the crystals in place.

k. The electrodes are set by first covering the walls of the electrode holes with conducting epoxy. The silver electrodes are then placed in the holes and slightly pressed down in order to get rid of any air bubbles.

l. When everything was been put in place the sample is then inspected to make sure that: first the crystals are not touching each other and second that there is no connection between the conducting epoxy used to connect all the crystals and the electrodes. Refer to Figure A.6.

m. Test and record all signals in the sample.
n. If the signals are satisfactory the rubber gaskets/ end caps can be glued to the end surfaces. K-20 was used to glue these two pieces together.

Figure A.6 Core sample with crystals and electrodes placed on their respective places. Notice that there is not connection in between the crystals as this could cause a shorting. Additionally there is no connection between the silver epoxy use to connect all of the crystals and the resistivity electrodes.

o. Attach connection pins to all of the cables (for both crystals and electrodes).

p. K-20 epoxy is used to glue the pins to the rubber gasket. Figure A.7

q. All of the signals for the sample are then tested and recorded.

r. Next the flexible epoxy jacket is prepared. For this experiment it was decided to use the EP1121 epoxy made by resin lab. The properties of the resin are given in Figure A.8. The preparation of this step is very critical as it affect all of the pressurized measurements directly. A poor epoxy job will lead to leaks in many cases.
Figure A.7 Rubber gaskets/ end caps are glued to the flat ends of the core. The individual cables are passing through the feed through in the end caps and pins are solder to them on the other end.

s. The mixture of the epoxy is 1A:1B meaning equal parts of resin and hardener. When mixing the mixture start with a maximum of 5 cm$^3$. Gently and slowly mix so that no bubbles are created in the process of mixing. This process is repeated until the desired volume of epoxy is obtained.

t. A clean overhead projector sheet was then wrapped around the core. A section was left open and the epoxy was poured. The core was left to dry for 48 hours.

u. After the core was prepared the sample was tested again. All the crystals were tested and recorded.
v. Cables were attached to the pin connectors. These cables will connect to the top of the vessel head.

w. Pore lines were attached. Refer to Figure A.9.

Figure A.9 An example of the final core set up.
x. Core was attached to the top of the pressure vessel.

y. Signals were tested and recorded.

z. Vessel was lowered down and pressure was increased to 50 psi. Signals were tested and recorded.

A.2 Sample Saturation under Pressure

The following steps show the methodology used to saturate the samples under pressure. The saturation was done in order to perform NMR measurements.

1. The first step is to make sure that all of the proper data such as dry weight has been recorded for the core samples that will be saturated.

2. The next step is to create a brine solution. In order to create an appropriate brine solution the correct amount of NaCl and distilled water must be used. The calculation is done by first multiplying the wanted concentration (in this study 20,000 ppm) by the volume of the distilled water (or solvent) which would give the moles of NaCl. The second step is to multiply the number of moles by the molar mass and this will yield the amount of NaCl that needs to be added to the distilled water.

3. The next step is to make that all of the vessels that will be used in the experiment are thoroughly clean. For this experiment two vessels where used, one was a transfer vessel which is used in order to avoid putting brine into the Isco pump and second a saturation vessel where the cores will be placed. The first step in the cleaning process is to use water and soap to clean the inside and outside of the vessel, the cleaning includes threads and any piece of pipe connected to the vessel. If the vessels has been in contact with any hydrocarbon fluids acetone must also be used to clean the vessels.

4. The next step is to inspect any O-rings, piston, and end connectors and to apply silicone grease as needed.

5. As mentioned earlier the transfer vessel is used in order to avoid damaging the Isco pump by using a brine solution. It acts as an intermediate between the water inside the Isco pump and the brine that will be used in the measurements. The transfer vessel is assembled by first inserting the piston inside the vessel (after inspection), fill the side
connected to the Isco pump with water, and fill the side connected to the pressure vessel with brine. The end caps are placed at each end.

6. Samples are placed on the saturation vessel and after checking the threads the end cap is placed.

7. In order to reduce the amount of air in the system, one of the first steps is to make sure that water in the Isco pump does not have air in it. This is done by first filling up the pump with water and then by closing both valves (inlet and outlet) pressure is applied (approximately 100 psi) and the valve connected to the water reservoir is slowly released. Precaution must be taken as pressure will be released from the valve. Protective equipment must be worn.

8. The next step is to set up the system by connecting all of the vessels and valves. Make sure that connections are not leaking.

9. Pull vacuum on the sample for a period of time (in this experiment vacuum was pulled for a total of 28 hours). This was done by connecting a vacuum pump (with liquid trap) to the top of the vessel. Close valve from the saturation vessel to vacuum pump. Turn off vacuum pump.

10. Vacuum must also be pulled on the brine solution. This is done by first making sure that the valve to the vessel is closed and that the vacuum pump has a liquid trap. Vacuum was pulled until brine was seen on the liquid trap of the vacuum pump.

11. The next step is to begin filling the saturation vessel. The first step is to make sure the Isco pump is full with fluid (distilled water for this experiment) and that there is enough fluid in the reservoir in case the volume in the pump is not enough. Make sure that the valve to the Isco pump reservoir is closed. The next step is to open up the valve that is connected to side of the transfer vessel that has distilled water, and then open up the valve of the transfer vessel that is connected to the saturation vessel. Finally, open the valve to the saturation vessel. Slowly begin to increase the pressure in the pump; the first step was to 25 psi. The Isco pump will continually pump fluid until that pressure is reached. In the meanwhile turn on vacuum pump (make sure that fluid trap is properly
working and that it is clean). Immediately after seeing fluid in the fluid trap of the vacuum pump, close the valve connecting the saturation vessel to the vacuum pump. Shortly after this the Isco pump will stop as it will have reached 25 psi.

12. Record the time, pressure, and volume in pump.

13. The next step is to set up a pressure gradient in the Isco pump. For this experiment the Isco pump was programmed to go from 25 psi to 600 psi by using a pressure gradient of 0.5 psi/min. Monitor the pressure increase at this point, if 600 psi is reached before the set time (about 20 hrs for this experiment) then this means that the transfer vessel ran out of all the saturating fluid (brine). In this case the transfer vessel must be filled again and steps 8 through 13 must be followed again.

14. Once the saturation vessel has reached 600 psi, monitor the change of volume in a constant basis (every two to three hours). If the volume does not change by more than 0.1 ml for at least 1 day then it was assumed that the cores had been saturated. For this experiment the samples were left 2 days after this scenario happened in order to make sure that the samples were completely saturated.

15. The last step is to very slowly decrease the pressure and remove sample. Samples were kept in a clean glass flask in the brine solution. The brine flask was kept in a vacuum chamber until NMR experiments were performed.

![Diagram of saturation measurements setup](image)

Figure A.10 Saturation Measurements Set Up.
A.3 Raw Ultrasonic Signals

This section of the appendix shows the waveforms for benchtop and pressurized conditions in different directions along the sample. For pressurized measurements the waveforms are given at multiple pressures and from loading cycles. Additionally, tables with a summary of velocity values are given.

A.3.1 Benchtop Measurements

![Figure A.11 Compressional wave propagation along four different directions for sample 5440 in Well 1B. Picture of core is included showing the directions.](image-url)
Figure A.12 Compressional wave propagation along four different directions for sample 7906 in Well 1B. Picture of core is included showing the directions.

Figure A.13 Compressional wave propagation along four different directions for sample 8539 in Well 1B. Picture of core is included showing the directions.
Figure A.14 Compressional wave propagation along four different directions for sample 8632 in Well 1B. Picture of core is included showing the directions.

Figure A.15 Compressional wave propagation along four different directions for sample 9097 in Well 1B. Picture of core is included showing the directions.
Figure A.16 Compressional wave propagation along four different directions for sample 9193 in Well 1B. Picture of core is included showing the directions.

Figure A.17 Compressional wave propagation along four different directions for sample 9447.5 in Well 1B. Picture of core is included showing the directions.
A.3.2 Pressurized Measurements

*Sample 7223.7*

Table A.1 Ultrasonic values obtained for sample 7223.7' in Well 1. Table shows the values for compressional and shear velocities in two different directions during pressure loading and unloading.

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<th>Shear Velocity (km/s)</th>
<th>Velocity Ratio (unitless)</th>
<th>Poisson's Ratio (0)</th>
<th>Poisson's Ratio (90)</th>
<th>Pressure (psi)</th>
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<td>Vp0</td>
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Figure A.18 Compressional wave propagation in Sample 7223.7 along P0 direction for different pressures steps. Colors show different pressure steps.

Figure A.19 Compressional wave propagation in Sample 7223.7 along P90 direction for different pressures steps. Colors show different pressure steps.
Figure A.20 Shear wave propagation in Sample 7223.7 along S0 direction for different pressures steps. Colors show different pressure steps.

Figure A.21 Shear wave propagation in Sample 7223.7 along S90 direction for different pressures steps. Colors show different pressure steps.
### Sample 7228.2

Table A.2 Ultrasonic values obtained for sample 7228.2’ in Well 1. Table shows the values for compressional and shear velocities in two different directions during pressure loading and unloading.

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<th>Shear Velocity (km/s)</th>
<th>Velocity Ratio (unitless)</th>
<th>Poisson's Ratio (0)</th>
<th>Poisson's Ratio (90)</th>
<th>Pressure (psi)</th>
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</thead>
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<td>Vs0</td>
<td>Vs90</td>
<td>Vp0/Vs0</td>
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Figure A.22 Compressional wave propagation in Sample 7228.2 along P0 direction for different pressures steps. Colors show different pressure steps.

Figure A.23 Compressional wave propagation in Sample 7228.2 along P90 direction for different pressures steps. Colors show different pressure steps.
Figure A.24  Shear wave propagation in Sample 7228.2 along S0 direction for different pressures steps. Colors show different pressure steps.

Figure A.25  Shear wave propagation in Sample 7228.2 along S90 direction for different pressures steps. Colors show different pressure steps.
**Sample 7626.3**

Table A.3  Ultrasonic values obtained for sample 7626.3’ in Well 1. Table shows the values for compressional and shear velocities in two different directions during pressure loading and unloading.

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<th>Shear Velocity (km/s)</th>
<th>Velocity Ratio (unitless)</th>
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Figure A.26 Compressional wave propagation in Sample 7626.3 along P0 direction for different pressures steps. Colors show different pressure steps.

Figure A.27 Compressional wave propagation in Sample 7626.3 along P90 direction for different pressures steps. Colors show different pressure steps.
Figure A.28 Shear wave propagation in Sample 7626.3 along S0 direction for different pressures steps. Colors show different pressure steps.

Figure A.29 Shear wave propagation in Sample 7626.3 along S90 direction for different pressures steps. Colors show different pressure steps.
Sample 7750.7

Table A.4 Ultrasonic values obtained for sample 7750.7’ in Well 1. Tables shows the values for compressional and shear velocities in two different directions during pressure loading and unloading.

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<tr>
<th>Compressional Velocity (km/s)</th>
<th>Shear Velocity (km/s)</th>
<th>Velocity Ratio (unitless)</th>
<th>Poisson's Ratio (0)</th>
<th>Poisson's Ratio (90)</th>
<th>Pressure (psi)</th>
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<td>Vs0</td>
<td>Vs90</td>
<td>Vp0/Vs0</td>
<td>Vp90/Vs90</td>
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</tbody>
</table>
Figure A.30  Compressional wave propagation in Sample 7750.7 along P0 direction for different pressures steps. Colors show different pressure steps.

Figure A.31  Shear wave propagation in Sample 7750.7 along S0 direction for different pressures steps. Colors show different pressure steps.
Figure A.32 Shear wave propagation in Sample 7750.7 along S90 direction for different pressures steps. Colors show different pressure steps.
**Sample 7751.8**

Table A.5 Ultrasonic values obtained for sample 7751.8’ in Well 1. Table shows the values for compressional and shear velocities in two different directions during pressure loading and unloading.

<table>
<thead>
<tr>
<th>Pressure (psi)</th>
<th>Compressional Velocity (km/s)</th>
<th>Shear Velocity (km/s)</th>
<th>Velocity Ratio (unitless)</th>
<th>Poisson’s Ratio (0)</th>
<th>Poisson’s Ratio (90)</th>
</tr>
</thead>
<tbody>
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</tr>
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</tr>
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<td>1.72</td>
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</tr>
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<tr>
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<td>1.75</td>
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</table>
Figure A.33 Compressional wave propagation in Sample 7751.8 along P0 direction for different pressures steps. Colors show different pressure steps.

Figure A.34 Compressional wave propagation in Sample 7751.8 along P90 direction for different pressures steps. Colors show different pressure steps.
Figure A.35  Shear wave propagation in Sample 7751.8 along S0 direction for different pressures steps. Colors show different pressure steps.

Figure A.36  Shear wave propagation in Sample 7751.8 along S90 direction for different pressures steps. Colors show different pressure steps.
Sample 8154.5

Table A.6 Ultrasonic values obtained for sample 8154.5’ in Well 1. Table shows the values for compressional and shear velocities in two different directions during pressure loading and unloading. Notice the negative values of Poisson’s Ratio; this shows that the data was unreliable for this core.

<table>
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<tr>
<th>Vp0 (km/s)</th>
<th>Vp90 (km/s)</th>
<th>Vs0 (km/s)</th>
<th>Vs90 (km/s)</th>
<th>Vp0/Vs0</th>
<th>Vp90/Vs90</th>
<th>Poisson's Ratio (0)</th>
<th>Poisson's Ratio (90)</th>
<th>Pressure (psi)</th>
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</thead>
</table>
Figure A.37 Compressional wave propagation in Sample 8154.5 along P0 direction for different pressures steps. Colors show different pressure steps.
APPENDIX B. NMR Measurements
Compiled from Magritek manual and collaboration from Milad Saidian and Evan MCCarney.

• The Rock Core Analyzer can be run in two interfaces, one is the standard interface and the other is the expert interface. For this study it was decided to use the expert interface as it gives access to the entire Prospa 3 package.

• There are 8 major steps for an NMR measurement.
  1. Obtain physical properties of the core.
     ▪ These properties will be length, diameter, and weight.
  2. Session start up and set up.
     ▪ When starting up a new session it is always a good idea to first select the root directory. In this root directory all the NMR data will be saved.
     ▪ A folder was created with the name of the project and each individual sample will have a folder inside the project older.
  3. Sample loading.
     ▪ Before loading the sample, the excess water was wiped off using a non-absorbent paper.
     ▪ The sample was then weighted.
     ▪ Weight was recorded and the sample was then loaded into the sample holder (make sure to check that there are no other samples inside the sample holder).
  4. Tuning of probe.
     ▪ The first step of the tune tuning of the probe process is to check the B1 frequency. The value should be close to 2 MHz
     ▪ The next step is to do a “tune a match experiment” and make sure to save the data into the project folder. This is done by opening the TuneNMatch experiment in the RCA menu. When the tune and match
process begins a window will appear with a curve on a reflected voltage (\% versus frequency (MHz).

- The curve will have a dip that can be optimized by adjusting the tune and match knobs that are on top of the magnet.
- The knobs will be adjusted until the reflected power is minimized at the magnet frequency, at that point the line will turn green.
- Finish the tune and match experiment by clicking on the button. The data will be saved on the specified folder.

5. Find 90 experiment

- The amount of power that is needed for a \(90^0\) RF pulse has been found to be probe and only slightly sample dependent.
- This type is not usually run on a constant basis. However, this step is absolutely necessary after the probe has been changed, for this study the probe was changed from the 1 MHz to 20 kHz.

6. Noise in the system.

- External noises in the system can be minimized by running a noise can. This scan will check that noise levels are at an acceptable level.
- For this instrument typical domains are 0.35 uV (for 1 MHz) and 0.06 uV (for 20 kHz).

7. T2 Experiment

- In order to start a T2 experiment the RCA menu is open.
- Select T2CPMG
- All the parameters must be open.
Figure B.1 T2CPMG experiment window from RCA menu. Notice all of the parameters needed for experiment.
### B.1 Acquisition Parameters

#### Table B.1 T2 Experiment Data Acquisition Parameters - Well 1 - Dry Sample

<table>
<thead>
<tr>
<th>Sample Depth</th>
<th>Repetition Time (ms)</th>
<th>90 Amplitude (dB)</th>
<th>180 Amplitude (dB0)</th>
<th>Pulse length (us)</th>
<th>Echo shift (us)</th>
<th>Echotime (us)</th>
<th>Number of echoes</th>
<th>Number of Scans</th>
<th>Signal to Noise Ratio</th>
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#### Table B.2 T2 Experiment Data Acquisition Parameters - Well 1B - Dry Sample

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<th>Pulse length (us)</th>
<th>Echo shift (us)</th>
<th>Echotime (us)</th>
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<th>Number of Scans</th>
<th>Signal to Noise Ratio</th>
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### Table B.3 T2 Experiment Data Acquisition Parameters - Well 1 - Saturated Sample

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<th>Echotime (us)</th>
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### Table B.4 T2 Experiment Data Acquisition Parameters - Well 1B - Saturated Sample

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<th>90 Amplitude (dB)</th>
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<th>Echo shift (us)</th>
<th>Echotime (us)</th>
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8. Analyzing T2 results

- The T2 data obtained in the experiment can be analyzed by using different mathematical inversions. Program provided by Magritek has four different analysis methods. The methods are exponential fit (exp), bi-exponential fit (bi-exp), Lexus (Butler Reeds and Dawson’s algorithm) and a non-negative least square fit, NNLS (based on Butler-Reid-Dawson).

- For this experiment it was decided to use the Lexus analysis. This method can provide logarithmic binning on data points, which allows very short and long relaxation times to be used, this means that it will produce better results for samples with very short relaxation times.

Figure B.2 T2 relaxation data with Lexus fit
B.2 NMR Porosity calculation

- Open data for calibration sample with a known fluid volume
- Set the x-axis to log by right clicking on axis and using “log/lin mapping”
- Select the data cursor
- Select the first point and read the value at the bottom to find the signal level
- Divide the signal level by the volume to get the calibration value
- Here the sample value is 20.5 mL and the signal is 22.5uV

\[ Cal = \frac{Signal}{Volume} = \frac{22.5\mu V}{20.5\text{mL}} = 1.11\mu V/\text{mL} \]

![Figure B.3](image)

Figure B.3 Calibration sample (fluid) data file with known fluid volume. Arrow points to the maximum value of the signal level.

- Right click on the data and save it to a vector
- Divide the y axis by the calibration factor to convert it to mL
- The data may look very similar if the calibration factor is near 1
- Plot the new data as show on the right to have incremental porosity in mL
- To convert to % porosity you will need to divide by the total volume of the sample
- Label the axes and title by right clicking on the axes and selecting the correct tabs
- Click apply after each to make sure the change applies
Figure B.4 Plot of sample data collected before and after diving by calibration factor obtained from fluid.

B.3 NMR Background Correction

- Load both the data set and background into two separate 1D windows.
- Right click on the data set and select copy trace data to vector.
- Click OK or rename the x and y variable then click OK.
- Select the background 1D window.
- Go to the macros menu of the 1D window and select filloutside1D.
- Select “End” as the Fill method and choose the new size to be equal to the size of the sample data set. Set the value to zero as shown below.

![Fill outside 1D plot](image)

- Repeat 2 and 3 for the background choosing different variable names such as BG for y.
- On the CLI type y_corr = y - BG
- Your difference data set is now y_corr.
- Right click on a 1D window that you want to display your data in and select “Display vector...”
- Select x for x and y_corr for y, then click Display and Exit.
- You can now save the plot using the save option or export using the export option and selecting the 1D. This should be documented in the manual and help.
• You can modify the title and axes labels by right clicking on them and filling out the dialog window.

Reliable Data Signals – Background Noise Lower than Core Signal Noise

Figure B.5  NMR Background Analysis for sample 5360 from Well 1B. Shows reliable data for analysis.

Figure B.6  NMR Background Analysis for sample 5477.3 from Well 1B. Shows slight reliable data for analysis.
Figure B.7  NMR Background Analysis for sample 7906 from Well 1B. Shows reliable data for analysis.

Figure B.8  NMR Background Analysis for sample 8272 from Well 1B. Shows slight reliable data for analysis.
Not Reliable Data Signals – Background Noise Higher than Core Signal Noise

Figure B.9  NMR Background Analysis for sample 8333 from Well 1B. Shows unreliable data for analysis.

Figure B.10  NMR Background Analysis for sample 9447.5 from Well 1B. Shows unreliable data for analysis.
Figure B.11 Relationship between mercury-injection pore size distribution and $T_2$ distribution for sample 7750.8 from well 1. The original mercury injection data was translated by using a $\rho_e$ of 1 um/sec.
Well 1B

Quartz Dominated

Figure B.12 Relationship between mercury-injection pore size distribution and $T_2$ distribution for sample 8935 from well 1B. The original mercury injection data was translated by using $\rho_e$ of 1.75 um/sec.
Figure B.13 Relationship between mercury-injection pore size distribution and $T_2$ distribution for sample 9193 from well 1B. The original mercury injection data was translated by using a $\rho_e$ of 5 um/sec.
Figure B.14 Relationship between mercury-injection pore size distribution and $T_2$ distribution for sample 8632 from well 1. The original mercury injection data was translated by using a $\rho_e$ of 1 um/sec.
Figure B.15  Relationship between mercury-injection pore size distribution and $T_2$ distribution for sample 8539 from well 1. The original mercury injection data was translated by using a $\rho_e$ of 1 um/sec.