Salt densities and velocities with application to Gulf of Mexico salt domes

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SUMMARY

We study the densties and elastic properties of rock salt from benchtop ultrasonic measurements, log data analysis in the Gulf Coast regions, and seismic survey designs, acquisition and interpretations over salt domes.

In the lab, we analyzed the composition, density, velocity, and stress effects of a variety of rock salt samples. The tested samples are from very different environment. Salt samples from the Gulf of Mexico region are largely isotropic with mixed orientations of micro-cracks and crystal aggregates. The Zipaquirá, colombia samples show velocity and density variations from their lamination of alternating layers of relatively pure halite and argillaceous halite. The Goderich, Canada halite crystals display distinct cubic anisotropy, with the elastic constants calculated as: C_{11}=48.7, C_{44}=13.1 and C_{12}=11.9. From a study of 142 log suites from boreholes drilled through salt in the Gulf of Mexico, we found that *P*-wave velocity $V_p(km/s)$ increases with depth $D(km)$ of the salt as: $V_p = 4.41 + 0.0104 \cdot D$, with the average standard deviation of 0.10 km/s. The salt electron density readings concentrate at 2.06 $\pm$ 0.1g/cm^3. These lab measurements and log data analyses provide further information on the elastic properties of salt to assist with velocity model building, synthetic seismogram generation, and understanding the elastic properties of halite.

A southwest-northeast trending gravity line was collected in the Pierce Junction salt dome, TX. The 2D and 3D velocity model is proposed by combining that with earlier seismic surveys, topography surveys as well as a east-west gravity profile. Both 2D and 3D seismic surveys can be designed based on such velocity model for the purpose of full coverage of the target zones. Gravity and elastic measurements complement each other to produce a more constrained subsurfece picture.

INTRODUCTION

With some of the world largest oil discoveries being located either below or close to salt bodies (Landrø et al., 2011), many studies have investigated the complexity of the salt bodies with respect to tectonics, stress effects, drilling hazards and anisotropy. Seismic imaging and interpretation of regions with salt structures can be challenging. Velocity model building relies on the comprehensive understanding of evaporite composition, properties, and tectonics.

Rock salt is ductile and deformable under overburden pressure and heat. With the relative low density (2.0 to 2.2 g/cm^3), salt tends to flow upwards and push the overlying layers. Dominant stress also plays an important role in guiding the flow direction. The relative ease with which salt moves upwards and laterally adds complexity to both shapes and elastic properties of salt formation under different tectonic regimes. Gravity and magnetics methods, which measure lateral changes in density and magnetic field can provide constrains for boundaries in complicated structures such as salt bodies.

ULTRASONIC LAB MEASUREMENTS

The ultrasonic pulse-transmission method is often used to find velocities in geologic materials (Vernik and Liu, 1997; Stewart et al., 2012). We conduct transmission traveltime recording by using vertical or horizontal pulse transducers (0.5-1 MHz) as sources and receivers (Figure 1). The tested samples are collected from various locations (Figure 2): Gulf of Mexico region (the Hockley salt mine, TX and the Bayou Corne salt dome, Louisiana), the Zipaquirá Salt Mine, Colombia and the Goderich salt mine, Ontario. From the X-ray powder diffraction (XRD) and inductively coupled plasma-mass spectrometry (ICP-MS) analysis, most of the samples are tested to be very pure halite (over 95%). The Zipaquirá salt samples, however, contain argillaceous halite laminations which are visible from the samples as well as in-situ.

Density and velocity are measured under room temperature and standard atmosphere pressure for all the samples first (Table 1, Table 2). The rock salt cores from the Gulf of Mexico areas (Hockley salt mine, TX and Bayou Corne salt dome, Louisiana) are generally isotropic from current measurements, with irregular crystals randomly distributed. The large velocity variations are observed from the Zipaquirá and Goderich salt samples. The Zipaquirá rock salt samples show the elastic properties variation due to the lamination. The interbedded argillaceous layer has lower velocity (4.01$\pm$0.03 km/s for *P*-wave and 2.39$\pm$0.01 km/s for *S*-wave) than the halite layer. The Goderich salt samples display anisotropy from their cubic crystalline structure. Velocities are measured with waves propagate in two sets of directions: along the direction of symmetric axes (X, Y and Z) and in the halfway between two symmetric axes (K). The calculated elastic constants are: C_{11} = 48.7, C_{44} = 13.1, and C_{12} = 11.9 (Zong et al., 2014).

Complementary tests under confining pressure from 0 - 4000 *psi* are conducted on Bayou Corne samples. The velocity generally increases when pressure is elevated (Figure 3). CT scanning shows that micro-fractures and cracks are closed under pressure, which explains the rapid velocity increment upon applying pressure (Figure 4).

WELL LOGS IN GULF OF MEXICO

More field data and empirical relationships are investigated through the study of 142 wells drilled in the Gulf coast (Figure 5). From the velocity-depth cross plot in Figure 6, we notice that there is a trend of velocity generally increasing with depth:

$$\mathbf{V} = 4.41 + 0.0104 \cdot D, \tag{1}$$

where V is the velocity (km/s) and D is the depth (km). The average standard deviation is 0.10 km/s (Zong et al., 2015).

The electron density readings range from 1.98 to 2.16 g/cm^3

with most data concentrating around 2.06 g/cm^3. We correct the bulk density by $\rho_b ulk = 1.044 \cdot \rho_e lectron$ and crossplot that with velocity (Figure 7). The color bar gives information of the velocity-density correlation likelihood. The outliers are likely contributed by different interbedded components, e.g., gypsum (V_p = 5.7 km/s, ρ = 2.3 g/cm^3), anhydrite (V_p = 6.5 km/s, ρ = 2.97 g/cm^3), sylvine (V_p = 3.5 km/s, ρ = 1.9 g/cm^3), etc..(Jones et al., 2014). For a better comparison, we plot both electron density reading and corrected bulk density data overlap with Gardners empirical velocity-density relationship plot in Figure 8. The original data match better with Gardner's prediction. However, the current data appears more like a cloud rather than a trend. Hopefully these empirical numbers would help with the salt velocity models building in the Gulf coast.

GRAVITY SURVEY AND MODEL BUILDING

A 2-D gravity survey was carried out over the Pierce Junction salt dome TX in 2013 by AGL. The data were collected along a southwest-northeast trending (18°) profile. The total length of the profile was 7600 m with 200 m station interval (Figure 9). The objective of the survey was to model the gravity data and obtain a north-south cross-section of the salt dome, in addition to the east-west cross-section drawn by Glass (1953). AGL's Scintrex CG-5 Autograv gravimeter, Garmin GPS, distance measurement tools, and safety equipment were used during the data acquisition. The graph of the raw gravity data was computed from topography survey and is shown in Figure 10. The gravity variation caused by lithology change can be revealed after removing the temporal and spatial effects (Figure 11). We applied drift and tide corrections to eliminate the time varying effects. Latitude, free-air, Bouguer, and terrain corrections are applied to remove spatial effects. A forward modeling was carried out by using GEOSOFT Oasis Montaj software (Figure 11). The typical US Gulf Coast sediment densities were used in the modeling stage (Table 3). Combining that with the documented velocity values showed in Table 4 for this area (Lash, 1980; Ewing et al., 1984; Castagna et al., 1985; Oezsen, 2004; Willis et al., 2006; Bain, 2010; Jiao, 2012). Both 2D and 3D interval velocity models are built as Figure 12.

CONCLUSIONS

Through this study, we have a better understanding of salt properties and have provided values for salt velocity modeling for pre-salt and sub-salt imaging in the Gulf of Mexico area. In terms of the anisotropy, the tested samples show three different scenarios. We observed the cubic anisotropy in the undeformed pure halite samples. The Louisiana salt cores show the slight velocity variation mainly due the alignment of deformed halite crystalline. The Hockley salt cores behave generally isotropic. The current results remind us that the isotropy assumption of salt formation should be carefully addressed during the velocity model building.

Compared with lab measurements, the field measurements provide a more realistic reference for building velocity model in specific environment with multiple influencing factors and other unknowns entailed (Gardner et al., 1974). We give an empirical relationship for velocity verses depth in Gulf of Mexico area from the log data analysis. Basically velocity increases slightly with depth. The correlation between density and velocity from the probability density plot would be useful for initial velocity model building. These results are representative for general Gulf of Mexico area.

For complex velocity variation areas such as salt domes, gravity survey provides a solution for obtaining velocity model. A series of synthetic seismic tests is able to be conducted on such model in order of designing the seismic surveys with optimum parameters and low cost.

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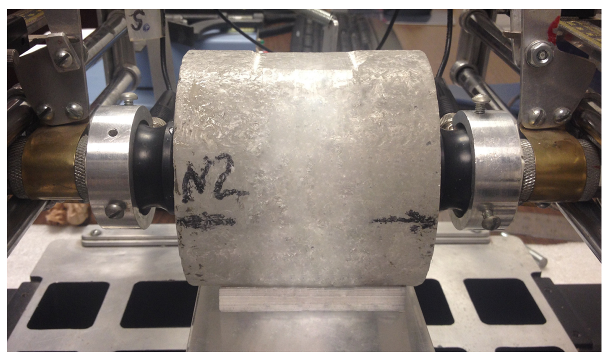


Figure 1: Samples are placed in between the ultrasonic source and receiver transducers using a couplant.

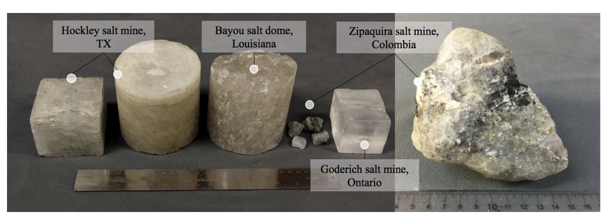
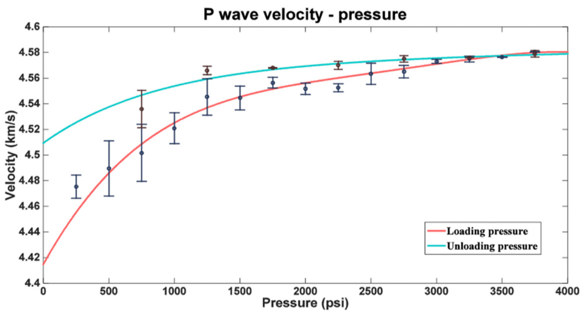
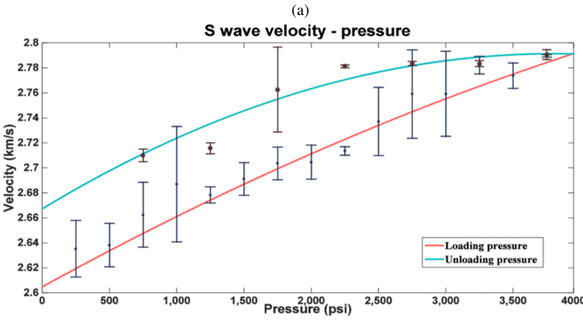


Figure 2: Rock salt tested samples from different areas (Hockley Salt Mine, Texas; Bayou Corne, Louisiana; Zipaquirá Salt Mine, Colombia; and Goderich, Ontario.).

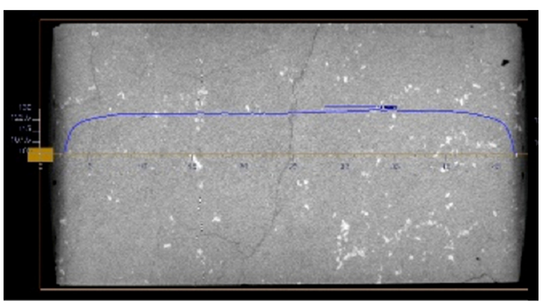


(a)

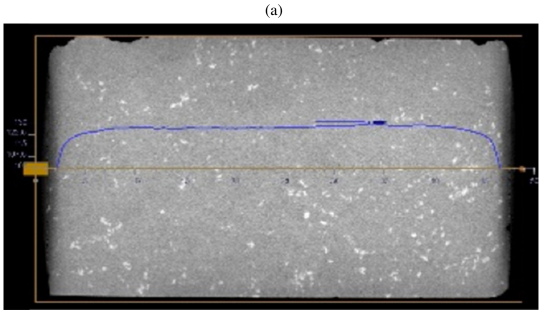


(b)

Figure 3: (a) and (b) The *P*- and *S*-wave velocities of Bayou Corne salt plug measured under confining pressure (Zong et al., 2015).



(a)



(b)

Figure 4: CT scanning results of Bayou Corne salt plug (Zong et al., 2015).
(a) Micro-fractures and cracks are visible before the confining pressure is applied.
(b) Most micro-fractures and cracks are closed after the confining pressure has been applied.

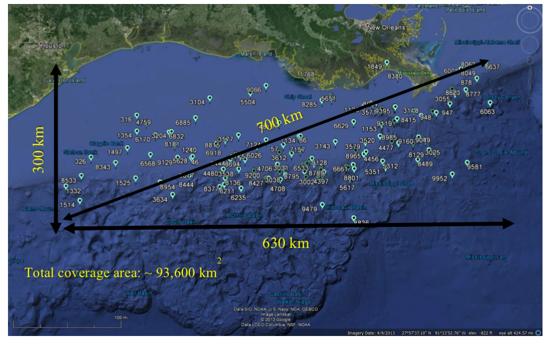


Figure 5: Well locations of this study, using 142 well-log suites.

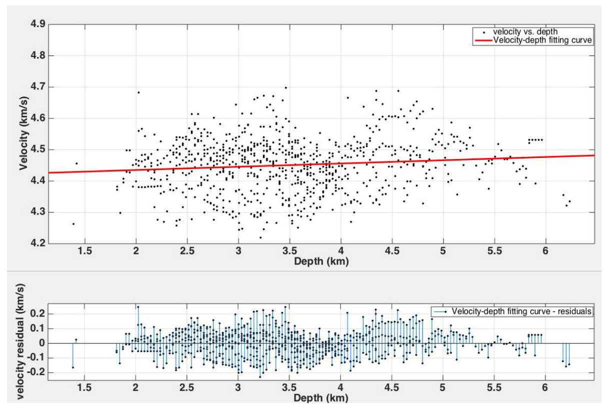


Figure 6: Top: Cross-plot of velocity-depth data from the logs. Red line is the fitted curve: $V_p = 4.41 + 0.0104 \cdot D$. Bottom: The residual of our fit with an averaged standard deviation of $0.10\ km/s$.

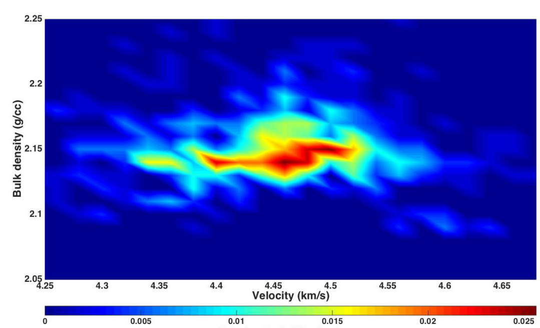


Figure 7: Cross-plot of corrected bulk density readings and velocity for salt intervals from the 142 log suites. The color bar is the probability density.

Sample locations	$V_p(km/s)$	$V_s(km/s)$	$\rho(g/cm^3)$
Hockley	4.64±0.09	2.70±0.05	2.18±0.01
Bayou Corne	4.45±0.02	2.59±0.03	2.15±0.01
Zipaquirá	4.19±0.18	2.46±0.12	2.10±0.18

Table 1: Average velocities and densities measured in salt samples.

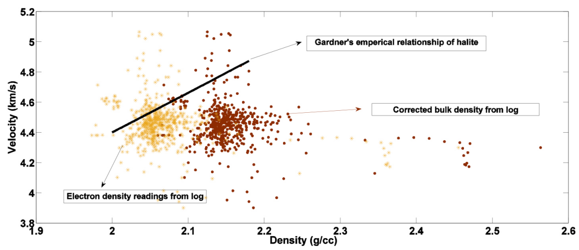


Figure 8: Comparison of log readings with Gardner's relationship. The black line is Gardners data, the yellow stars are electron density readings from the log and the maroon dots are calculated bulk density from the log readings.

Figure 9: Location of the gravity survey. Blue polygon represents the estimated top of the salt boundary (Huang, 2012).

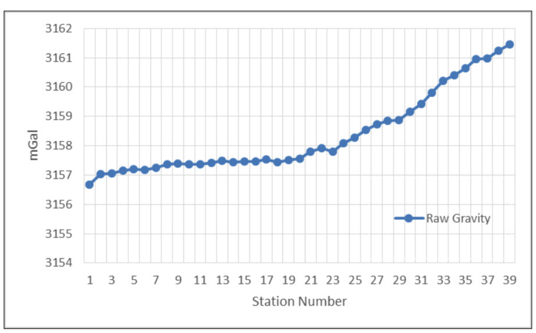


Figure 10: The raw gravity data of SW-NE line. The total length of the profile was 7600 m with 200 m station interval.

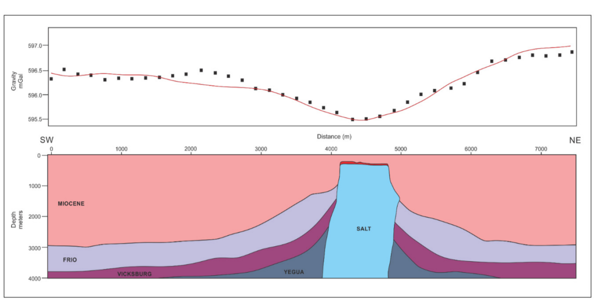
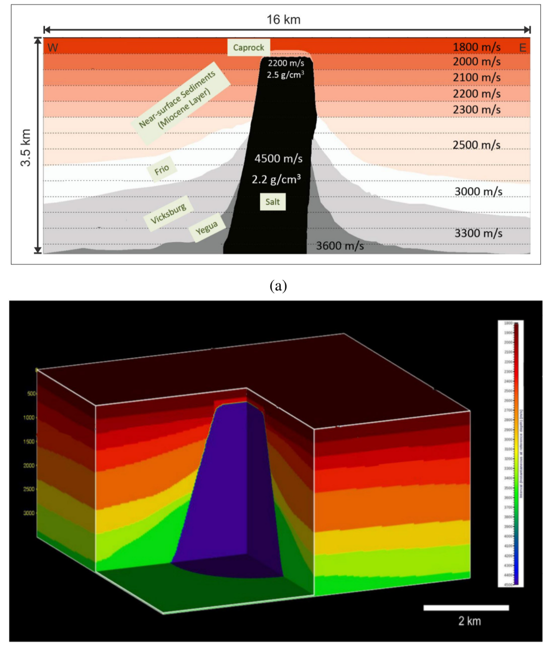


Figure 11: Gravity model of SW-NE profile. Black dots and red line represent the observed and calculated gravity, respectively. Vertical exaggeration of model is 0.5.



(a)

(b)

Figure 12: (a) and (b) 2D and 3D interval velocity models of Pierce Junction Salt Dome.

Wave propagation direction	$V_p(km/s)$	$V_s(km/s)$
X	4.75±0.01	2.46±0.01
Y	4.75±0.01	2.46±0.01
Z	4.76±0.01	2.46±0.01
K: Half way between X and Y	4.44±0.01	2.92±0.01
		2.47±0.01

Table 2: Velocities measured in Goderich salt samples. X, Y and Z indicate the directions that wave propagating along symmetric axes. K indicates the direction that wave propagating in half way between X and Y.

Layer	Salt	Caprock	Miocene
Density(g/cm^3)	2.20	2.60	2.25
Layer	Frio	Vicksburg	Yegua
Density(g/cm^3)	2.35	2.43	2.50

Table 3: Layers and densities that are used in gravity modeling (Prieto, 2000).

Layer	$V_p(km/s)$	$V_s(km/s)$	V_p/V_s
Salt	4.5	2.25	2
Caprock	2.2	1.1	2
Miocene	1.8-2.5	0.6-1	3-2.5
Frio	3	1.27	2.37
Vicksburg	3.3	1.32	2.37
Yegua	3.6	1.52	2.37

Table 4: Velocity information in Pierce Junction salt dome, TX (Lash, 1980; Ewing et al., 1984; Castagna et al., 1985; Oezsen, 2004; Willis et al., 2006; Bain, 2010; Jiao, 2012).

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