Attenuation of rock salt:
Gulf of Mexico core measurements and a VSP survey

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Outline

Introduction and motivations

Ultrasonic lab Q measurements
  Gulf coast salt cores

Field Q estimations
  A VSP survey in Markham salt dome, TX

Conclusions
Attenuation mechanism

- Geometrical spreading

\[ Q = \frac{\Delta E}{2\pi \cdot E} = \frac{\Delta A}{\pi \cdot A} \]

- Scattering

- Intrinsic attenuation or anelasticity
Motivations of the salt study

Seal rock
studyblue.com

Storage
© KBB Underground Technologies

Mining
saltassociation.co.uk
Attenuation modeling

Synthetic wave propagations in rock salt

Synthetic traces - Z component

Q=50
Q=250
Q estimation – spectral ratio method

(a) Aluminum standard

Sample $Q$

Aluminum $Q_0 \approx +\infty$

(b) Multi travel lengths

$A(f) = G(x)e^{-\alpha(f)x}e^{i(2\pi ft-\kappa x)}$

$$\ln\left(\frac{A}{A_0}\right) = \left(\frac{\pi t_0}{Q_0} - \frac{\pi t}{Q}\right)f + \ln\left(\frac{G}{G_0}\right)$$

(Johnston, 1978)

$$\ln\left(\frac{A}{A_0}\right) = -\frac{\pi t}{Q}f + \ln\left(\frac{G}{G_0}\right)$$

Measurement Slope Intercept

$$\ln\left(\frac{A}{A_0}\right) = -\frac{\pi}{Q}(t_0 - t)f + \ln\left(\frac{G}{G_0}\right)$$
GoM rock salt core

Hockley, TX

Bayou Corne, LA

Examples of the measured rock salt samples

<table>
<thead>
<tr>
<th>Elements</th>
<th>Hockley (%)</th>
<th>Bayou Corne (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na</td>
<td>37.70 ± 0.20</td>
<td>39.53 ± 0.27</td>
</tr>
<tr>
<td>Ca</td>
<td>96.1%</td>
<td>99.6%</td>
</tr>
<tr>
<td>S</td>
<td></td>
<td>NaCl</td>
</tr>
<tr>
<td>Mg</td>
<td>0.0014 ± 0.0010</td>
<td>0.0041 ± 0.0033</td>
</tr>
<tr>
<td>Sr</td>
<td>0.0087 ± 0.0001</td>
<td>0.0049 ± 0.0001</td>
</tr>
</tbody>
</table>
Experimental apparatus for ultrasonic measurements


**Attenuation of GoM rock salt – spectral ratio method**

\[ \ln \left( \frac{A}{A_0} \right) = -\frac{\pi t}{Q} f + \ln \left( \frac{G}{G_0} \right) \]

**Measurement**  | **Slope** | **Intercept**
--- | --- | ---
Attenuation of GoM rock salt – spectral ratio method

**Benchtop measurements:**
- \( H_1 \): \( Q_p: 32 \pm 4, Q_s: 34 \pm 3 \)
- \( H_2 \): \( Q_p: 43 \pm 6, Q_s: 34 \pm 4 \)
Attenuation of GoM rock salt – spectral ratio method

\[ \ln \left( \frac{A}{A_0} \right) = -\frac{\pi}{Q} (t_0 - t)f + \ln \left( \frac{G}{G_0} \right) \]

Measurement \quad Slope \quad Intercept

Benchtop measurements

\[ Q_p : 57 \pm 13, \; Q_s : 41 \pm 2 \]

\[ H_1 \text{ vs. } H_2 \text{ PP-1MHz} \]

Received Pulse

Spectral Amplitude

\[ \ln(H_1/H_2) \]
Temperature dependence – Bayou Corne, Louisiana

Relative Q variations under varying temperature
Relative Q variations under varying pressure
Attenuation – pressure and temperature dependence

Vp vs. Pressure, Temperature

Qp vs. Pressure, Temperature

24°C(75°F)-loading  24°C(75°F-unloading)  38°C(100°F)  66°C(150°F)  93°C(200°F)
Pressure healing & thermal cracking

CT Scanning of the test sample before and after pressure loading

Thermal cracks on the surface of rock salt under increasing temperature (Chen et al., 2015)
Attenuation – pressure and temperature dependence

\[ \log_{10} Q_P^p = 54 \log_{10} V_{Pp}^p - 34 \]
\[ R^2 = 0.7 \]

\[ \log_{10} Q_L^p = 53 \log_{10} V_{Pp}^L - 33 \]
\[ R^2 = 0.84 \]

\[ \ln Q_P = 53 \cdot \ln V_P - 33 \]
\[ R^2 = 0.84 \]

\[ \log_{10} Q_s = 28 \log_{10} V_s - 10 \]
\[ R^2 = 0.4 \]

\[ \ln Q_s = 28 \cdot \ln V_s - 10 \]
\[ R^2 = 0.4 \]
A typical GoM salt dome

Well A (KB = 25.9 m)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma Ray (API)</td>
<td>0</td>
</tr>
<tr>
<td>Caliper (in)</td>
<td>100</td>
</tr>
<tr>
<td>Resistivity (ohmm)</td>
<td>26.02</td>
</tr>
<tr>
<td>Density (g/cc)</td>
<td>2.570</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>8</td>
</tr>
</tbody>
</table>

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**Check-shot data** — velocity profile

- **P-wave:** ~4570 m/s
  - In salt

- **S-wave:** ~2560 m/s
  - In salt

*Interval velocity*
Check-shot data - Qp

P-wave first arrival picking and velocity profile

Flattened down-going P-waves

Spectra ratio and Q estimation
Check-shot data - Qs

1. S-wave first arrival picking and velocity profile
2. Flattened down-going S-waves
3. Spectra ratio and Q estimation

- Time (ms) and Velocity (FT/S)
- Depth (FT) and Frequency (Hz)
- Cumulative Attenuation

Values:
- Depth: 2914, 4000, 5000, 6075, 6000, 6745
- Time: 100 to 1200 ms
- Velocity: 10 to 80 FT/S
- Frequency: 10 to 70 Hz
- Cumulative Attenuation: 0.005, 0.015, 0.025, 0.035

- Qs: 31.6, 10.9, 19.7, 83.4, 16.5
Attenuation – pressure and temperature dependence

**Qp vs. Vp**

\[ \log_{10} Q_{P_{\text{Popp}}} = 54 \log_{10} V_{P_{\text{Popp}}} - 34 \]
\[ R^2 = 0.7 \]

\[ \log_{10} Q_{P_L} = 53 \log_{10} V_{P_L} - 33 \]
\[ R^2 = 0.84 \]

**Qs vs. Vs**

\[ \log_{10} Q_{S} = 28 \log_{10} V_{S} - 10 \]
\[ R^2 = 0.4 \]

- Popp et al., 01: Fitting line (Popp et al.)
- \( L_1 \): Fitting line \( L_1 \)
- VSP Markham
Conclusions

• Increase pressure elevates both velocity and Q;
• Increase temperature decreases velocity and Q;
• Q vs. V: $\ln Q_P = 53 \cdot \ln V_P - 33$; $\ln Q_S = 28 \cdot \ln V_S - 10$.

✓ A better understanding of the elastic behaviors of rock salt is provided;
✓ Empirical values and relationships are summarized for direct application.
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