Rock physics of a deep overburden shale

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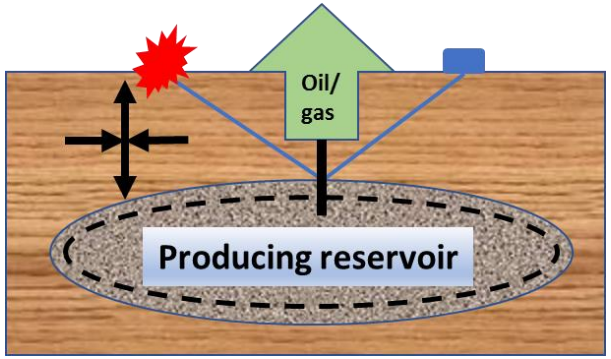
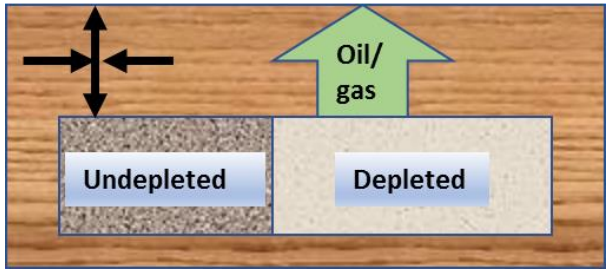
4D of overburden: Motivation

- **4D Seismic attributes** (time shifts, reflectivity changes) in the **overburden** depend on changes in **stress** and **pore pressure** caused by reservoir depletion/inflation.
- **Seismic** waves are travelling through a **massive** & **changing overburden**
- Early identification of **safety issues** for drilling and injection operations
- **Improved recovery** (optimized infill drilling): prevent undepleted pockets



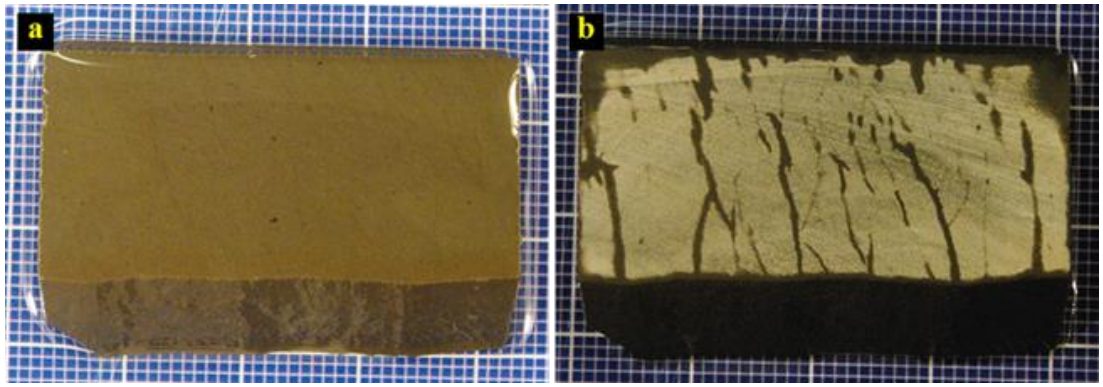


About the shale

- **Overburden shale** from the **deepwater Gulf of Mexico** cored at **6400 m** true vertical depth (subsea)

- Porosity: 15 %

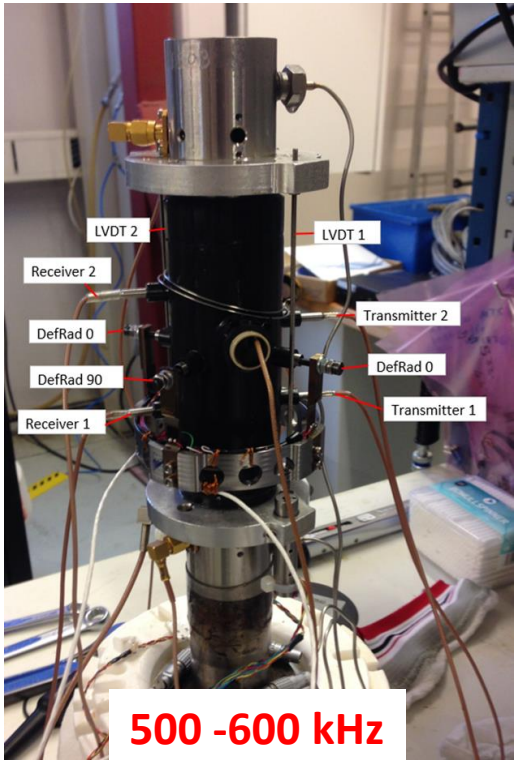
- Mineralogy dominated by clay minerals (57 wt%)



Laboratory tests

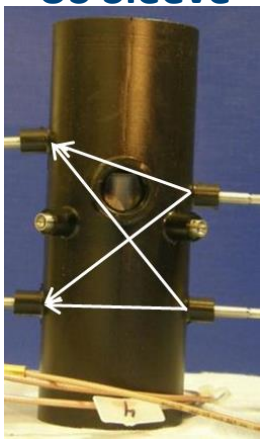
- **Multistage ultrasonic tests**
  - **Static** and **dynamic** properties in **multiple orientations**
- **Low-frequency tests**
  - Closing the gap between static and ultrasonic measurements
  - … at seismic frequencies

Ultrasonic stack



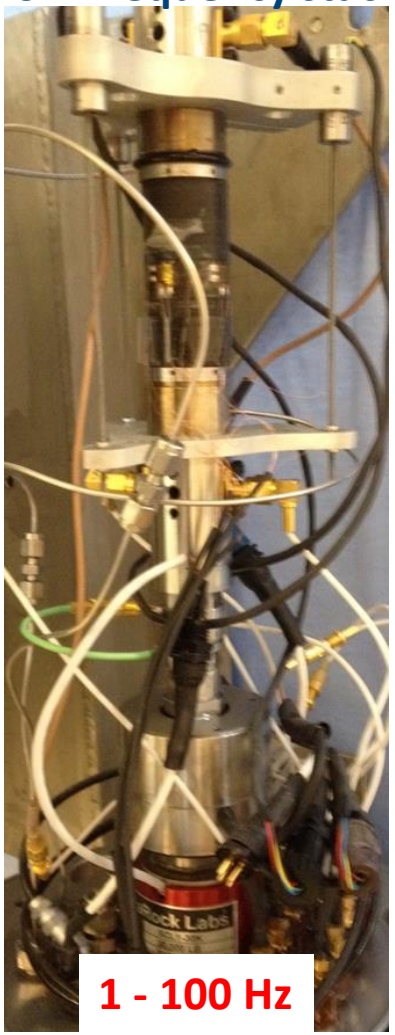
500 -600 kHz

US Sleeve



500 -600 kHz

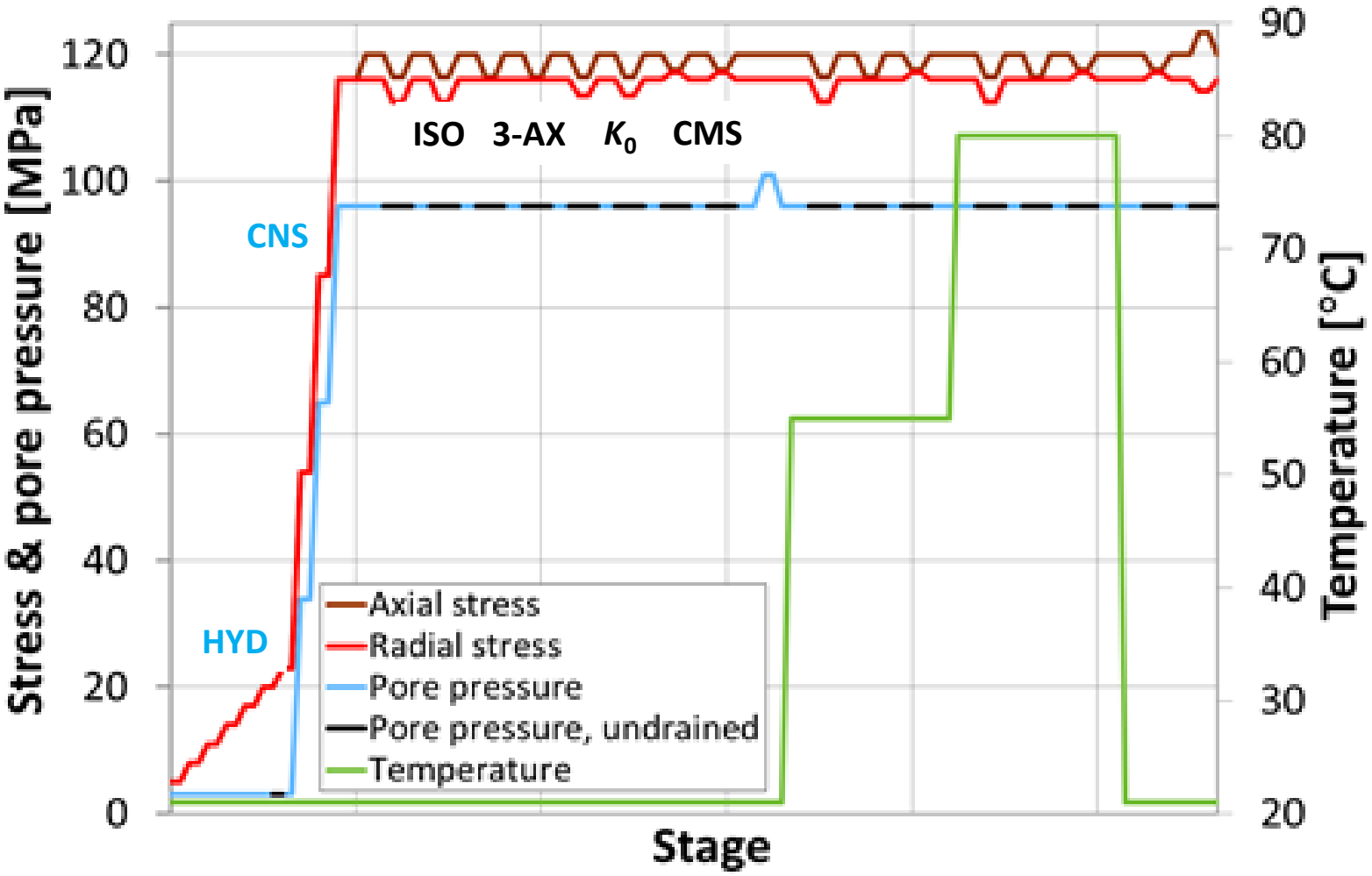
Low-frequency stack



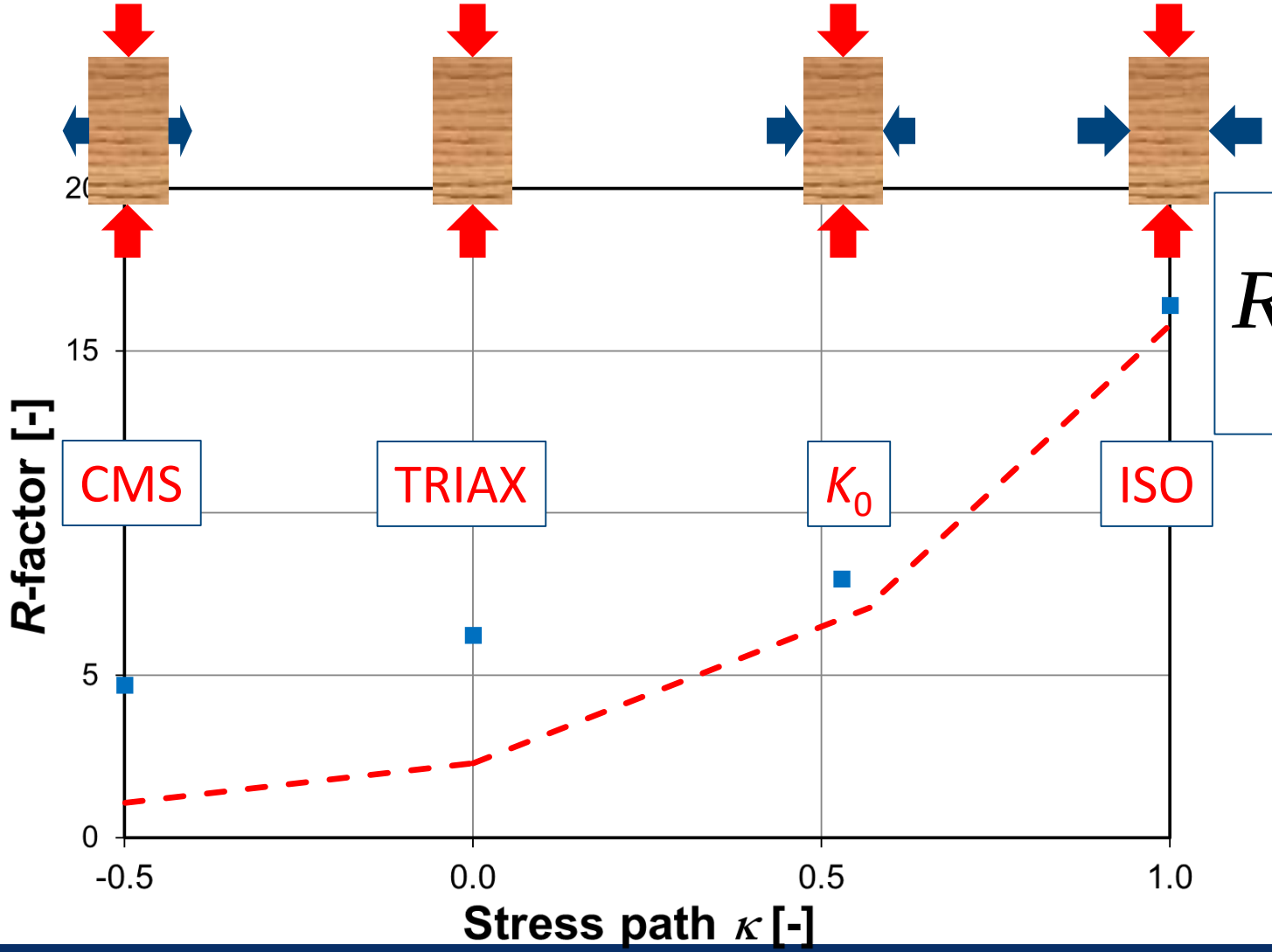
1 - 100 Hz

Full static & dynamic TI description obtained

Ultrasonic test: schematic protocol



Stress path dependence on velocity: *R*-factor



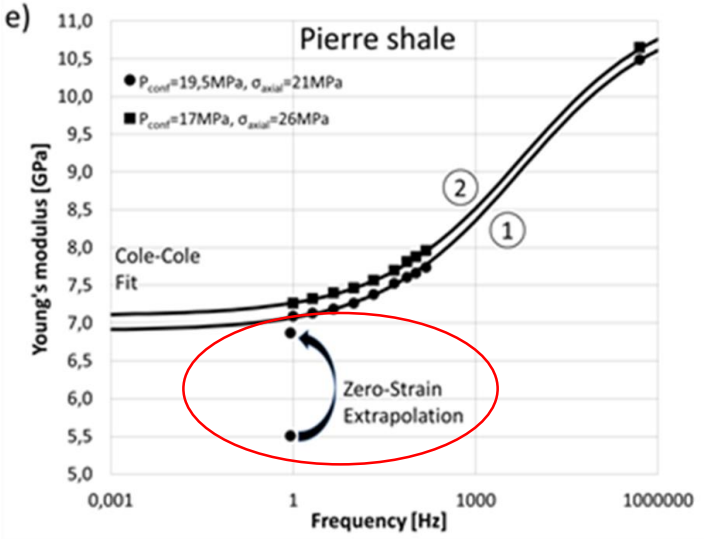
$$R = \frac{\Delta V_{Pz}}{V_{Pz}\varepsilon_z}$$

$$\kappa = \frac{\Delta \sigma_r}{\Delta \sigma_z}$$

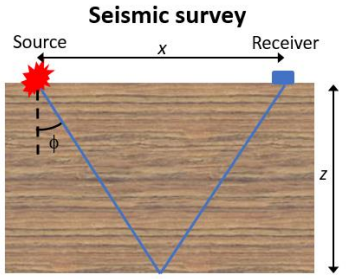
Dispersion

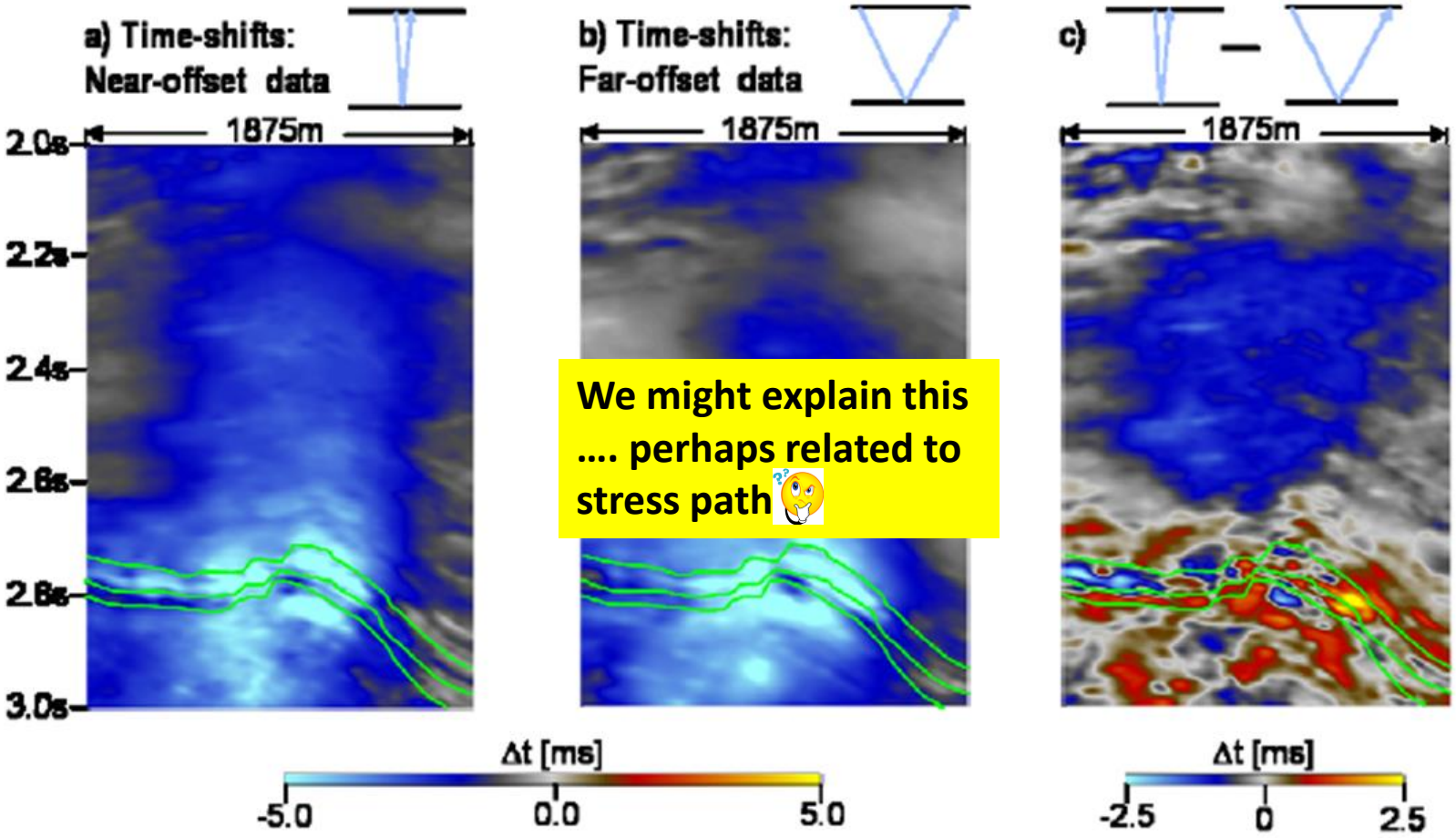
	Temperature [°C]	Frequency [Hz]	C_{11} [GPa]	C_{33} [GPa]	C_{13} [GPa]	C_{44} [GPa]	C_{66} [GPa]
Ultrasonic	24	$5 \cdot 10^5$	39.8	29.3	12.8	7.4	12.7
Ultrasonic	80	$5 \cdot 10^5$	35.9	27.7	13.9	6.9	-
Low-frequency	≈24 (ambient)	1	25.7	21.6	13.1	5.1	6.8
Static	≈24 (ambient)	-	24.2	21.1	11.2	5.7	7.0

- Principal elastic moduli exhibit **dispersion**
- **Significant reduction** of dynamic moduli at **elevated temperatures**
- **Static and low-frequency moduli are very close**, indicating **small non-elastic static compliance**. This is in contrast to other shales, where the non-elastic static compliance may be significant



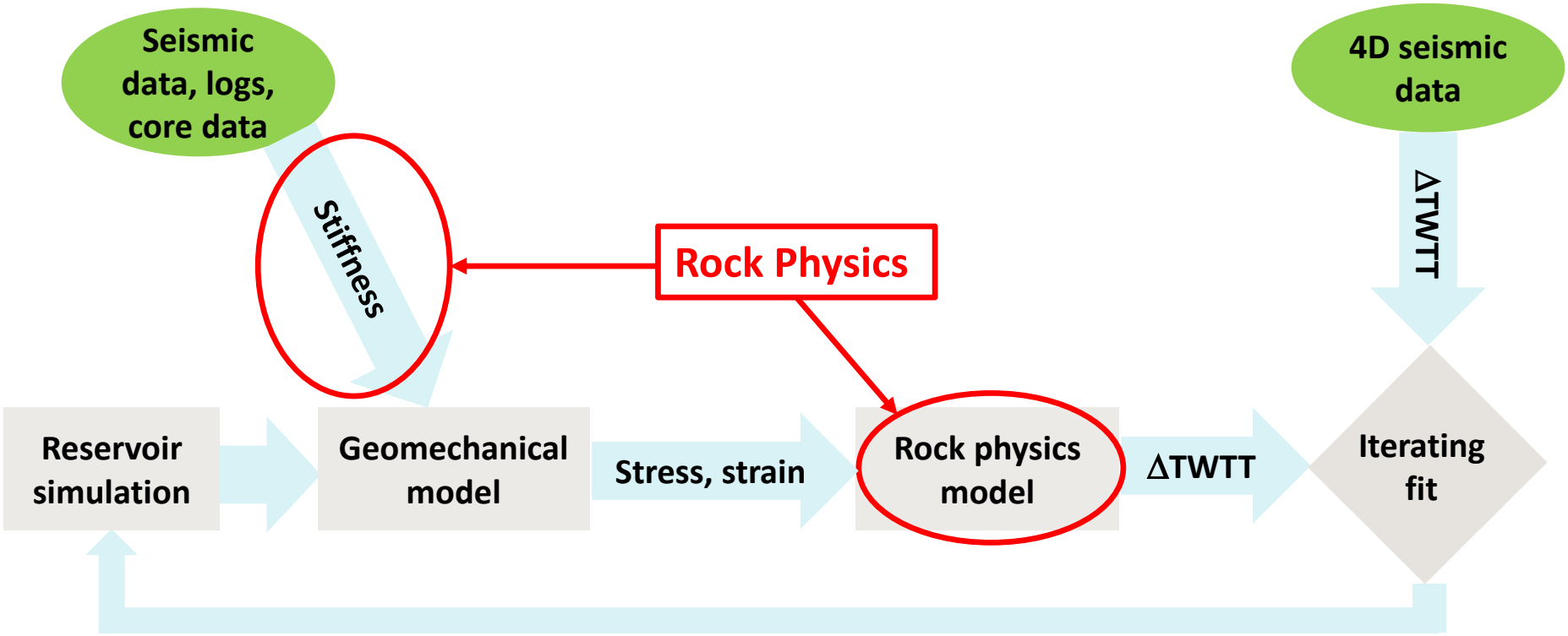
Application:
time-shift around depleting reservoir





North Sea Chalk reservoir – South Arne (Herwanger et al., 2007)

Application: 4D geomechanical modelling workflow



Summary

- **MULTISTAGE SHALE TESTS**: Complete **TI-stiffness** – **static** & **dynamic** - is determined
- The **strain sensitivity** (*R*-factor) has a **significant dependence on stress path**
- **Static** & **low-frequency moduli** are **similar**, indicate a competent shale with **negligible non-elasticity**
- **Angular dependence** of **4D time-shifts** may be a key to understand subsurface
- **Rock physics** is a **essential** component of the (4D) **geomechanical workflow**

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