Presentation Outline

- Introduction to Borehole Seismology
  - Why downhole?
  - Challenges and State of the Art

- Case Studies of Downhole Passive Seismic Monitoring
  - Induced seismicity at the Berlin geothermal field in El Salvador
  - Seismic monitoring of CO₂ storage and leakage at the Penn West EOR pilot (CA)

Concluding Remarks

Passive Seismic Monitoring: Motivation

- Earthquake magnitude (Richter scale)
  - Magnitude -2 / -1
  - Magnitude 7+
- Rupture surface
  - m²
  - >10³ km²
- Slip
  - mm
  - m

... detect the small ones
... better understand the large ones

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Earthquake Magnitude Ranges

<table>
<thead>
<tr>
<th>Magnitude range</th>
<th>Class</th>
<th>Length Scale</th>
<th>Displacement Scale</th>
<th>Frequency Scale</th>
<th>Seismic Moment*</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 – 10</td>
<td>Great</td>
<td>100-1000 km</td>
<td>0.4-40 m</td>
<td>0.001-0.1 Hz</td>
<td>mMKI-KMKI</td>
</tr>
<tr>
<td>6 – 8</td>
<td>Large</td>
<td>10-100 km</td>
<td>0.4-4 m</td>
<td>0.01-1 Hz</td>
<td>mKI-KKI</td>
</tr>
<tr>
<td>4 – 6</td>
<td>Moderate</td>
<td>1-10 km</td>
<td>0.4-40 cm</td>
<td>0.1-10 Hz</td>
<td>mKI-KKI</td>
</tr>
<tr>
<td>2 – 4</td>
<td>Small</td>
<td>1-1 km</td>
<td>0.4-40 mm</td>
<td>1-100 Hz</td>
<td>mKI-KKI</td>
</tr>
<tr>
<td>0 – 2</td>
<td>Micro**</td>
<td>1-100 m</td>
<td>0.4-4 mm</td>
<td>10-1000 Hz</td>
<td>1mKI-1mKI</td>
</tr>
<tr>
<td>-2 – 0</td>
<td>Nano</td>
<td>1-10 m</td>
<td>0.4-4 m</td>
<td>0.1-10 Hz</td>
<td>1mKI-1mKI</td>
</tr>
<tr>
<td>-4 – 2</td>
<td>Pico</td>
<td>0.1-1 m</td>
<td>0.4-4 mm</td>
<td>1-100 Hz</td>
<td>1mKI-1mKI</td>
</tr>
<tr>
<td>-6 – 4</td>
<td>Femto</td>
<td>1-10 cm</td>
<td>0.4-4 mm</td>
<td>10-1000 Hz</td>
<td>1mKI-1mKI</td>
</tr>
<tr>
<td>-8 – 6</td>
<td>Atto</td>
<td>1-10 mm</td>
<td>0.4-4 mm</td>
<td>1-100 MHz</td>
<td>1mKI-1mKI</td>
</tr>
</tbody>
</table>

Length and displacement approx. and appropriate for stress drops of 3 MPa

* 1 Aki is defined as $10^{18}$ Nm and named after Keiiti Aki who pioneered the use of seismic moment in theory and practice

** the term 'microearthquake' traditionally refers to $M<3$

Why Going Downhole?

- Drilling is expensive (in oil/gas industry drilling costs are >10 times the costs for pre-site surveys...).
- Drilling is risky and logistically extremely difficult. Downhole instruments need to operate at elevated pressure and temperature conditions.

BUT: Downhole seismic monitoring...

- allows to monitor at substantially reduced noise conditions thereby improving signal-to-noise ratio, magnitude detection threshold and precision of hypocenter determination.
- allows to broaden the frequency band of the recorded wavefield through recording also higher frequency contents.

HOWEVER: challenges in borehole seismology are a secure deployment of sensors (ensuring good coupling to the formation), safe data transmission to the surface, formation pressure/temperature/fluids.

Coupling of Borehole Seismometers

A good coupling of the sensors to the casing/formation is essential to generate reasonably good data quality.

This can be achieved through:

- Sand back-filling sensors at the base of the borehole (temporary or permanent)
- Cementing sensors in borehole or behind casing (permanent)
- Mechanical coupling of the sensor to the borehole wall or casing (mostly temporary)
Orientation of Borehole Seismometers

- No direct influence on orientation of sensors in borehole although essential.
- Sensors need to be vertically oriented within a few degree (or: gimbled sensor).
- Horizontal orientation can be determined through check shots (provides also feedback on sensor quality, coupling and formation velocity).

Obtaining High-Frequency Signals

- A typical frequency band of a seismic surface station extends up to ~100Hz.
- Higher frequencies are not seen due to attenuation in the shallow formation.

500Hz Data: Filtered 10Hz, 2s
Signal-To-Noise Improvement With Depth

- Quality of seismic recordings to a large extent is defined by the noise conditions at the sensor.
- Noise conditions improve substantially with depth.
- Involving drilling costs several hundreds of meters represent an optimum for the return on investment in downhole passive seismic monitoring.

(Malin, pers. comm.)

Downhole Seismology in Fundamental Research

- Since first seismic networks in 1910/20s systematic densification (regional/global). Today $M_c \leq 2$ in western US, Japan, western Europe.
- 1986: Installation of the Parkfield High Resolution Seismic Network (HRSN): Depth of sensors 65-550 m (mostly 250 m), data sampled at 250 Hz.

(P. Rutledge et al., BSSA, 1998)

Downhole Seismic Monitoring in Industry

- Mostly short-term deployments for downhole seismic monitoring of reservoir stimulation (hydrocarbon, geothermal, shale gas reservoirs).
- Usually seismometer strings in one or several monitoring wells close to reservoir.

Downhole Seismology in Japan: Station Distribution

- High sensitivity borehole stations, typically at 100 m depth

(Okada et al., EPS, 2004)

(Kwiatek et al., Acta Geophys., 2010)
Case study 1:
Monitoring Induced Seismicity in the Berlin Geothermal Field, El Salvador

Borehole Seismometer Network
- 12 borehole sensors (nat. frequencies 1/4, 5/5, 5/30 Hz) sampled 24-3000 Hz.
- 3 stimulation campaigns of 3 weeks each at 2 different depth intervals.

Relevance of Applying state-of-the-art Processing Techniques: Relative Relocation
- Application of hypoDD technique (Waldhauser/Ellsworth, 2001) to traveltime picks.
- Systematic shift of hypocenter locations towards the geothermal field (wrt initial absolute locations).
- Strong clustering of events around injection wells.
- Clear relation between seismic events and stimulation.
Relevance of Applying state-of-the-art Processing Techniques: Cluster Analysis

- Application of waveform cross-correlation technique to determine signal similarity at individual borehole sensors.
- Identification of 9 event families displaying similar rupture processes.
- Focus on seismicity at well TR8A in the following (deep blue family).

- Temporal migration of seismicity away from the reservoir towards a fault plane.
- Abrupt increase of event magnitudes and change of migration during shut-in.

- While good quality data is a pre-requisite for any study, state of the art evaluation methods are essential to obtain optimum and reliable results.
- Relative relocation of hypocenters allows to identify a systematic migration of events towards and along mapped fault planes, probably initiated by the elevated downhole pressure during injection.
- Larger magnitude events and seismicity clusters are observed during shut-in phases.
- Seismicity occurs in previously active areas only once the earlier maximum downhole pressure is exceeded (Kaiser effect).
Case study 2: Downhole passive seismic monitoring of CO₂ storage and leakage in the Penn West EOR pilot

Passive Seismic Monitoring of CO₂ Storage

- Passive Seismic Monitoring (PSM) is a frequently used technique to study natural and fluid-injection induced microseismicity along fault zones and in hydrocarbon and geothermal reservoirs.
- Monitoring induced seismicity in the frame of CO₂ storage is still in its infancy and has not yet been addressed systematically despite its great potential.
- We report on PSM in the Pembina Oil Field to analyze CO₂ leakage and to potentially characterize the CO₂ storage reservoir using induced microseismicity.

The Penn West CO₂ Injection Project

- Location: Pembina Oil Field, western Canada; EOR-Project.
- Monitoring well at 350 m distance from injector well (I2) but only 35 m away from producer well P1.

Penn West Downhole Geophone Array

- Instrumentation:
  - Geophone
  - Pressure/Temperature
  - Fluid sample
- Lithology:
  - Belly River
  - Wapiabi
  - Cardium (CO₂ reservoir)
  - Blackstone
- Geophone arrangement:
  - 8 three-component geophones
  - sensor spacing 20 m at 1500 to 1640 m depth
  - 24 Hz natural frequency
  - 1 kHz sampling frequency
Objectives: Microseismic and Leakage Monitoring

- Wellhead aperture / pressure fluctuations
- CO₂ / CH₄ bubbling at the surface
- Waveform processing of continuous data
- Detection of microseismicity / CO₂ signals
- Interpretation of the results

Spectral Analysis of Waveform Recordings

- Absence of typical signatures of microseismic events in spectograms of continuous data
- Dominant energy up to 200 Hz, clear indication of 50Hz signals and multiples
- No obvious correlation between individual sensors
- Useful tool to quantify signal quality of individual sensors

Analysis of Noise Levels at Individual Sensors

- Systematic search for noise level changes framing the time of a known CO₂ leakage (outburst within monitoring well)
- Result: Clear increase of the noise level during relevant time. But...

Noise level during ‘CO₂ Accident’

... detected noise level increase is not simultaneous.
Penn West Study: Lessons Learnt...

No evidence found for induced microseismic events at $M_w > -1$.

Frequency content:
- Mostly in $[0, 50]$ Hz.
- Abundant signals with energy up to 500 Hz.

Noise analysis:
- Study of reliability of each sensor.
- Identification of signals related with the CO2/CH4 outflow.

STA/LTA:
- Numerous potential events found but too weak to be further analyzed.

Low-frequency signals:
- Observed signals not mature enough to verify occurrence of low-frequency events during injection.

Case study 3:
Downhole passive seismic monitoring of natural microseismicity at the Marmara Seismic Gap, NW Turkey – the GONAF project.

Some General Conclusions

- Recent developments in downhole passive seismic monitoring technology allow to record high-quality data sets of microseismicity with the potential of addressing various relevant seismological topics.

- Case studies from passive seismic monitoring were discussed stressing that Basic and Applied Seismology are generally strongly interconnected addressing similar topics.

- Future challenges in passive seismic monitoring are intensifying the (permanent) deployment of downhole seismic instrumentation ensuring long-term operation at improved noise conditions, recording also the higher frequencies of the seismic wave field.

Thank you for your attention!