Engineered Geothermal at Otaniemi and Basel: “end”-members in drilling and induced seismicity?

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and
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In December 2006, a 5.5 km deep, rotary drilled, million-liter, brine-injection under the city of Basel, Switzerland, induced an M3.4. The result was a several million Euro road-bump for EU EGS. The aim of the injection was to create a single, ~km square, fracture system in which water could be circulated and heated for both electrical power generation and municipal district heating. Now 10 years, on Basel has become the international by-word for EGS induced-earthquake show-stoppers.

Set against this background, *st1 Deep Heat*, a joint venture with the Scandinavian petroleum distribution company *st1*, is attempting a slightly deeper, but much smaller volume and rate stimulation, district heating EGS development. The development is located on the Otaniemi campus of Aalto University, immediately west of Helsinki, Finland.

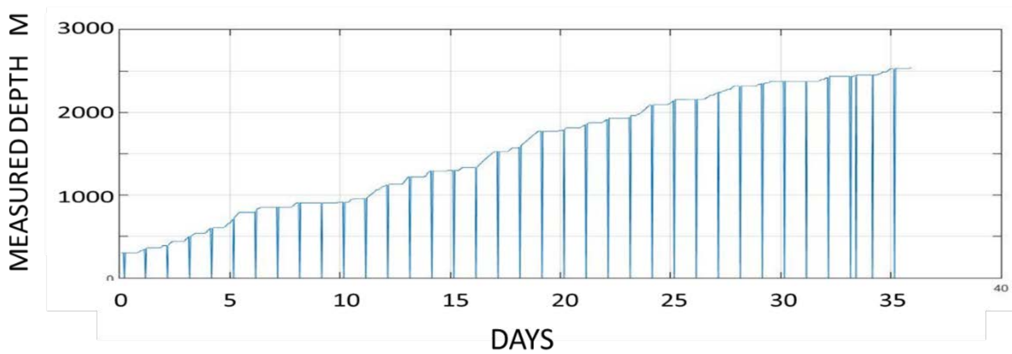
In this case the initial stimulation well was first air hammered 4500 m, setting a Scandinavian drilling record for both total depth and a one-day run of 252 m. Water hammer drilling was then tested to continue deeper, but after a 3-bit run yielded only 60 m of hole, a switch was made to rotary drilling. Deviation to ~30° was also begun. At 5020 m a highly fracture zone required extensive cementing, taking up 3 weeks of drilling effort. A similar zone was encountered at 5250 m, taking up another week. But, despite these time losses, it is now evident that there are permeable fracture systems at depth.

At the moment, straight hole drilling continues at ~35° with the aim of reaching a measured depth of 6500 m. Our R&D venture was selected for the seismic monitoring of both Basel and Otaniemi. At Basel, we installed six, 0.35 to 2.4 km deep, stations of downhole 2 Hz seismometers and 4-g accelerometers. At Otaniemi we are completing a 11-station net of 0.35 to 1.2 km deep, 4.5 Hz seismometers. We are also a 2240 to 2680 m deep, 12-level seismic VSP array at the drill site.

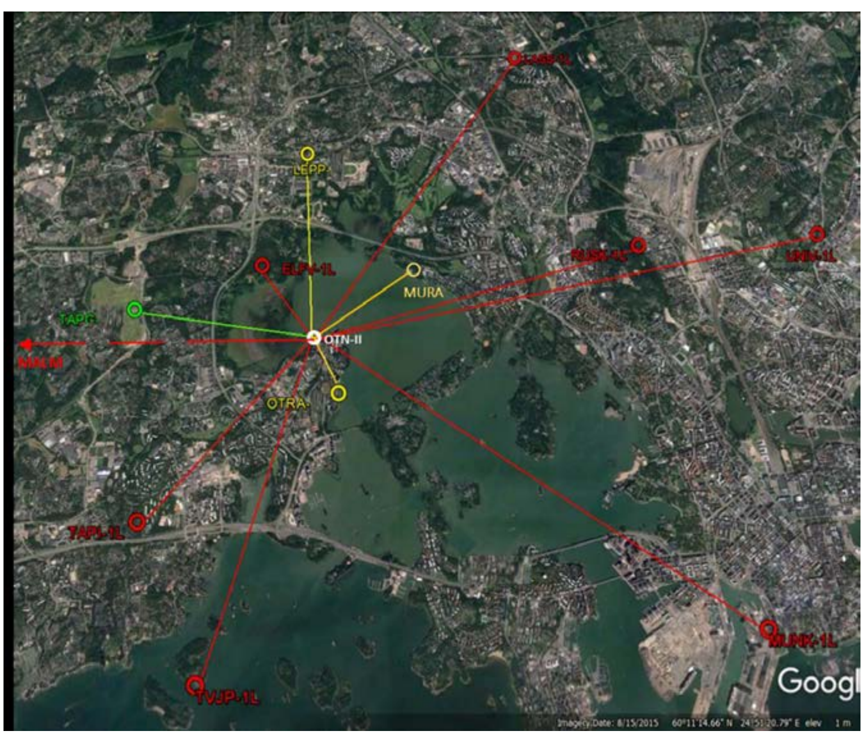
A swarm of induced microearthquakes occurred during casing-cementing at both Basel and Otaniemi. But this appears likely to be the only induced-seismicity parallel between the two projects. Not only are the stimulation and traffic-light monitoring plans end-members, the tectonic settings are entirely different: a continental rift versus isostatic rebounding crust. The rocks in Finland are cold, only ~20°C/km. The Otaniemi wells have remained circular to less than a percent, suggesting low horizontal shear stress. The stimulation is scheduled for Dec/Jan 2018, a few days before the SMU meeting. Will the stimulation produce enough pressure to open fractures and induce a felt earthquake? We are planning to report on these efforts at the meeting.

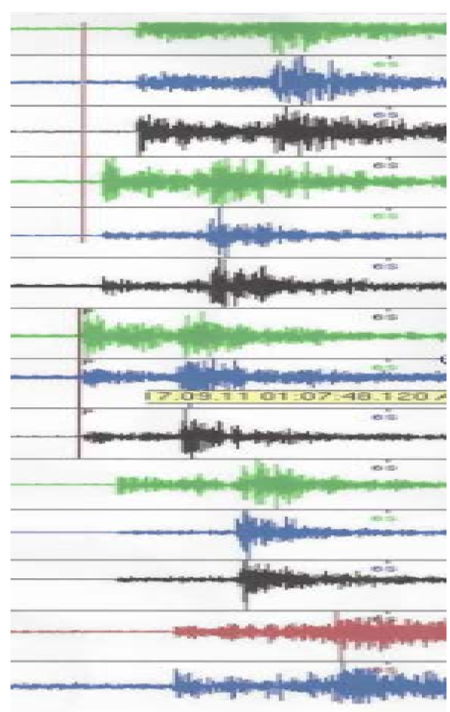
The Innova rig, 307 mm air hammer and cuttings

Air hammer drilling rate



Seismic Monitoring Net (drill site at OTN-III) and a cementing induced microearthquake (0.5 s window)





Advanced Seismic Instrumentation & Research LLC

SMU Power Plays Conf.

12 Jan 2017

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"End"-members in drilling and induced seismicity?

Matt Siegler (SMU)

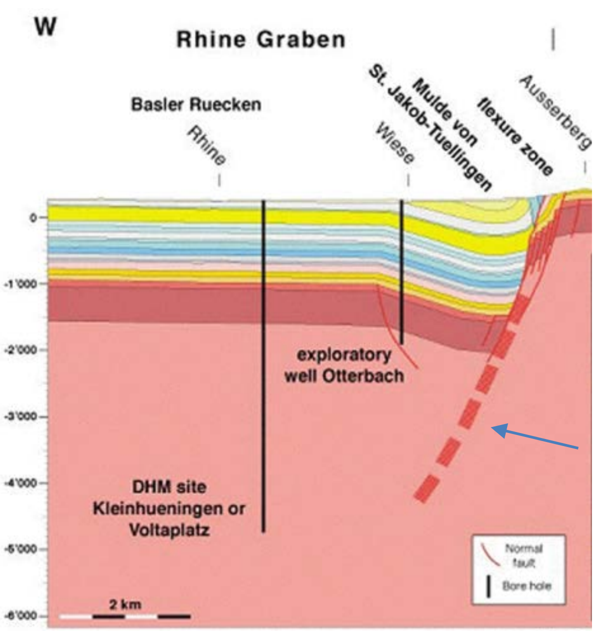
speaking for:

PE Malin et al.

(GFZ – Seismomechanics

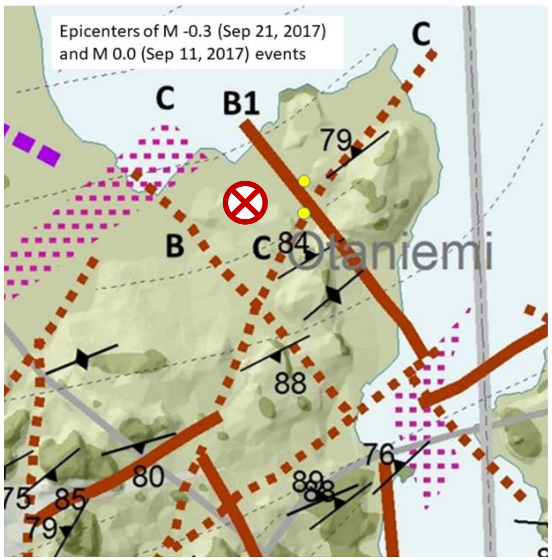
Advanced Seismic Instrumentation and Research)

Basel - Switzerland (2006 – "€20M")	Otaniemi/Espoo - Finland (2018 – "€30M")
Swiss Federal Office of Energy project	Joint ***st1*** (O&G) and *Fortum* (municipal Heat)
Contracted to Geothermal Explorers	Operators: ***st1 Deep Heat*** *Oy*
Single large fracture flow system in ~ 200 C	Close spaced double well system ~ 100 C
Primary direct use for municipal heating Secondary power for pumps Production from ~ 5 km	Primary direct use for municipal heating Secondary power for pumps ? Production from ~ 6 km

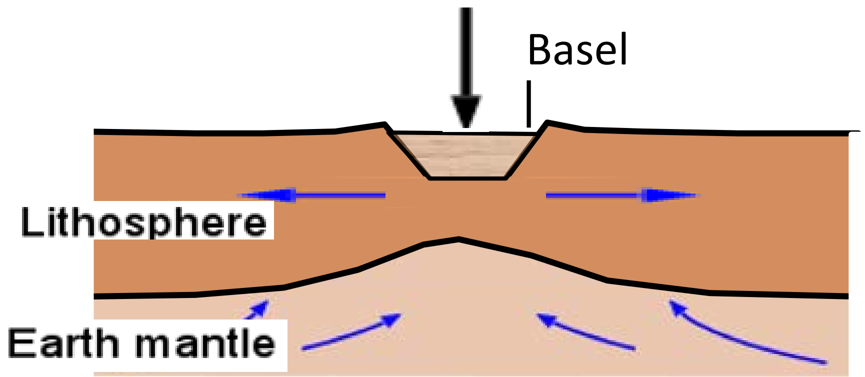


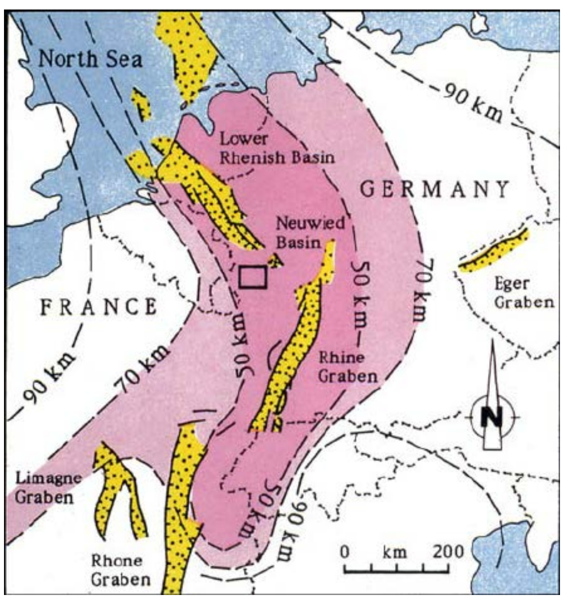
Rift Boundary Fault

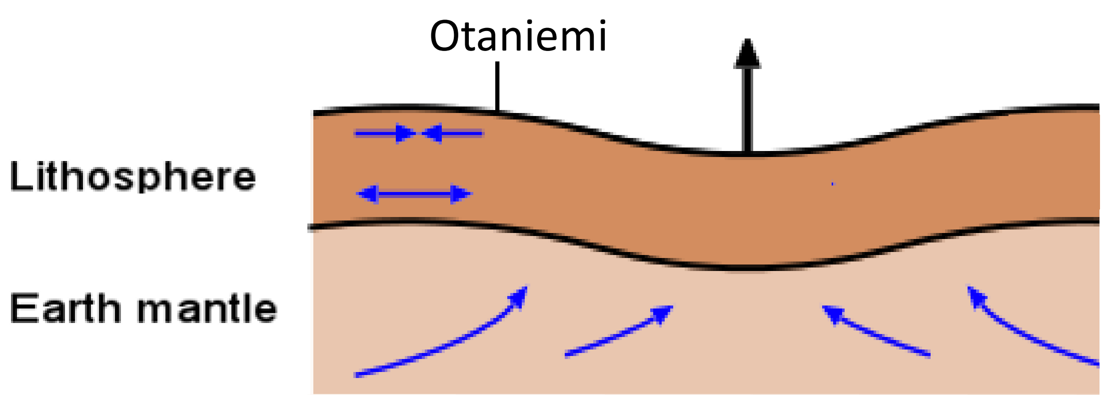
Fenno-Scandian Shield Faults



Induced Seismicity: The difference in geological settings

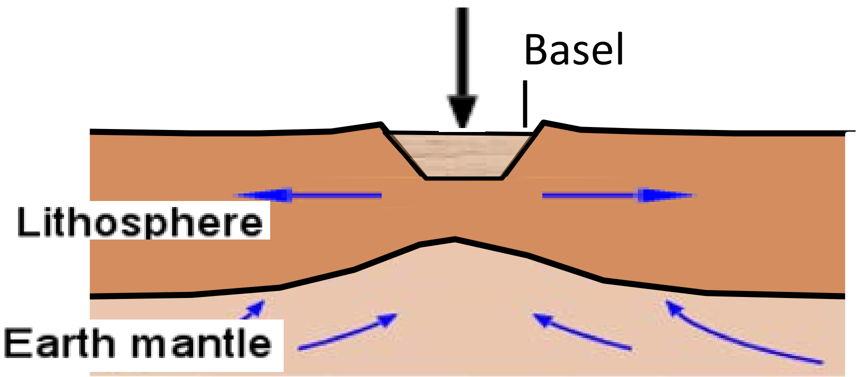






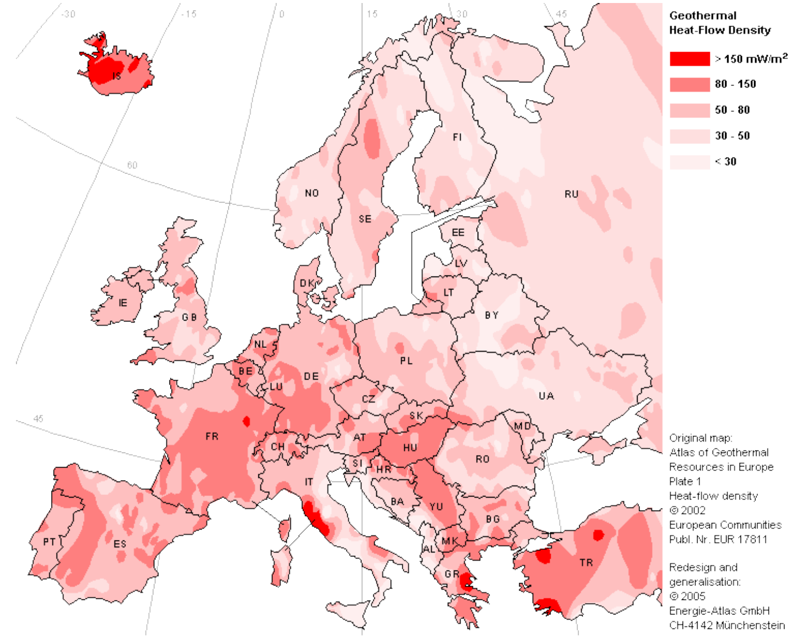
Induced Seismicity: The difference in geological settings

Basel → Rift Subsidence

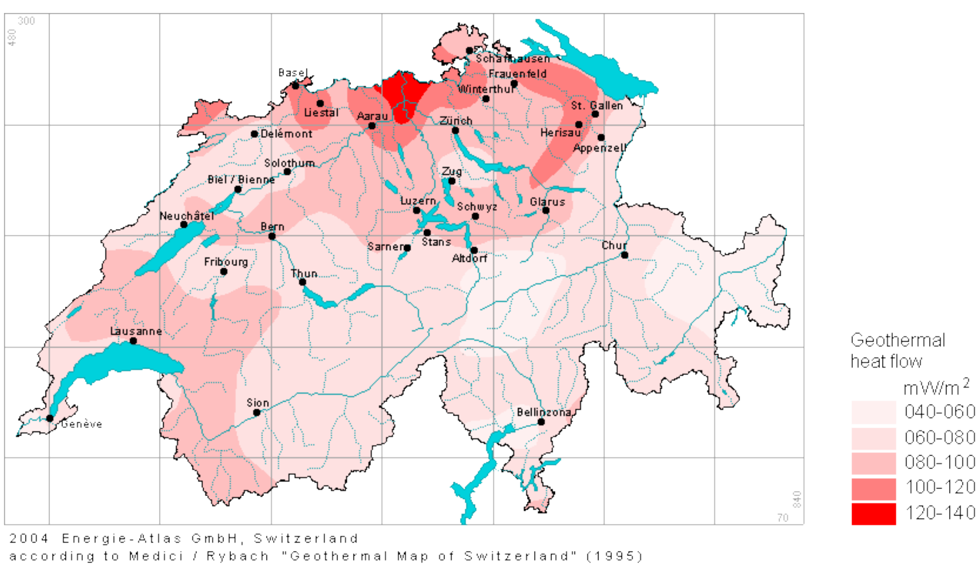


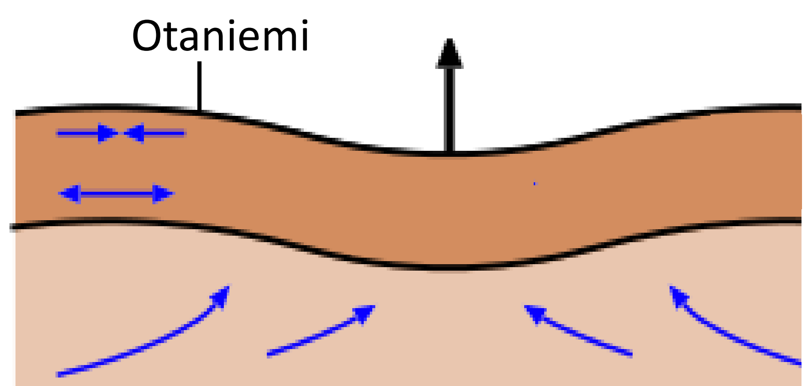
Extension

Mmax ~ 6.5



Otaniemi → Glacial Rebound





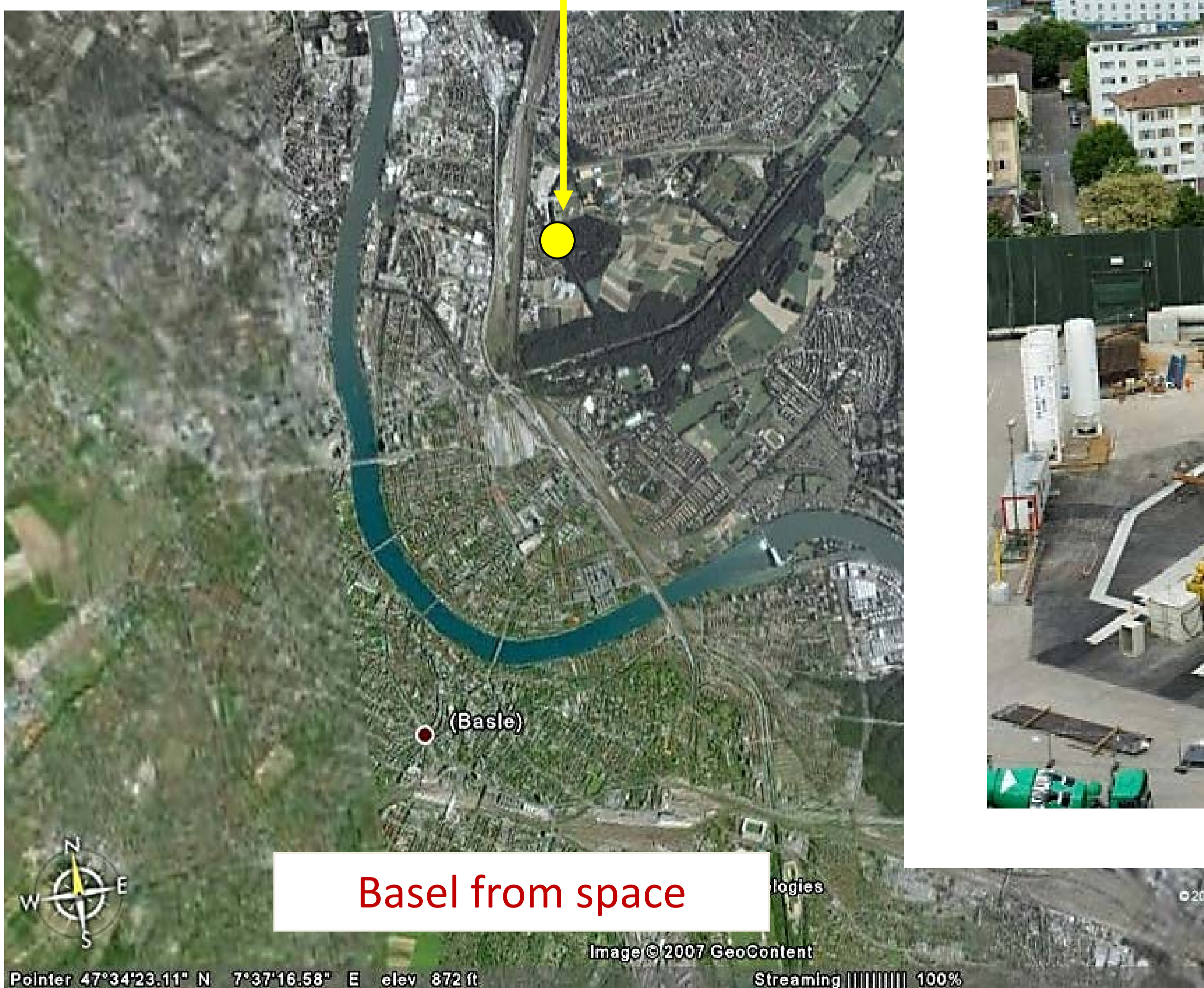
Flexture

Mmax ~ 2.7

2006 - A Critical EU EGS Project in

Downtown Basel, Switzerland!

5.5 km deep municipal heating wells



Basel from space

Rotary/mud drilling:

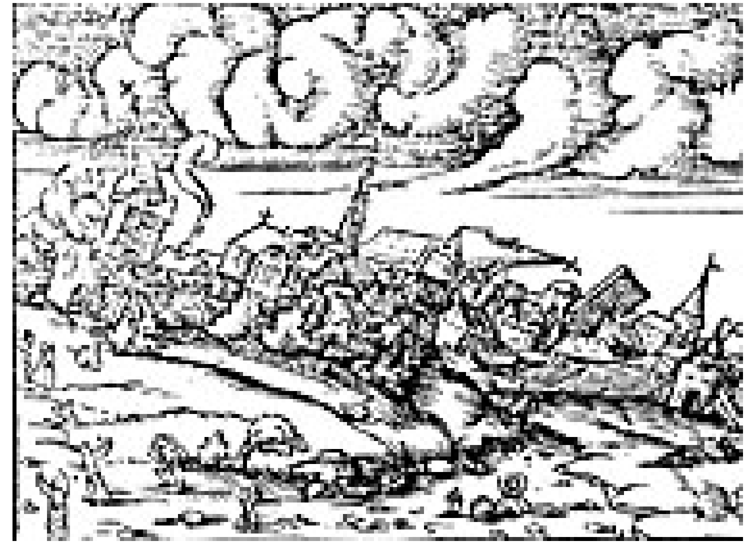
1-5 m/hr

swissinfo.ch

October 18, 2006

Basel emergency officials participate in earthquake preparedness exercise ....

.... on anniversary of 1356 **M6.5.**



December 9, 2006

Man-made tremor shakes Basel!

Drilling for geothermal power triggers small earthquake, causes minor damage...

.... City prosecutor launches investigation to find if the company should pay repairs.....

What happened?

.....25,000 Earthquakes!

9 hrs after shut in

Number of event per hour:

Detected

Located

Legal Limit = 3.4

Magnitude

Magnitude

2018 - Another Critical EGS Project

Aalto University, Finland!

6.4 km (target) deep municipal heating wells

Otaniemi from space

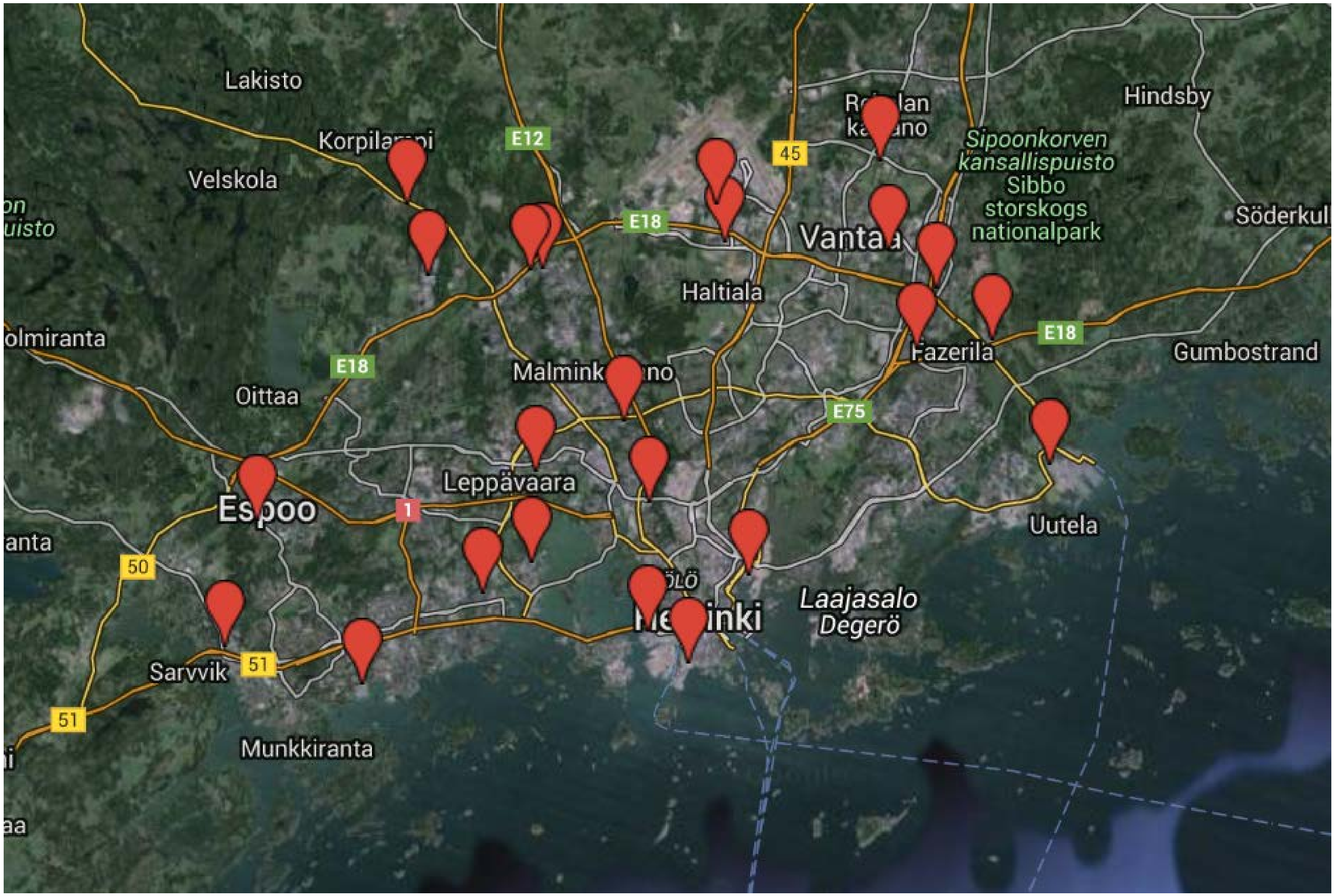
Air hammer drilling:

5-10 m/hr

(to 4500 m – rotary/mud to 5700 m)

The Otaniemi District Heat Plant – circa 1949

Helsinki District Heat Plant Network - ***all fossil fuel fired***



More than 20 metropolitan Helsinki ….and more than 300 in the country

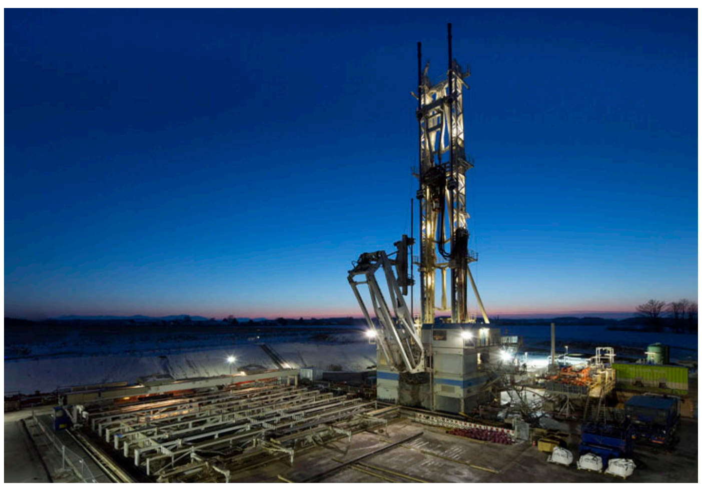
Air Hammer Drilling

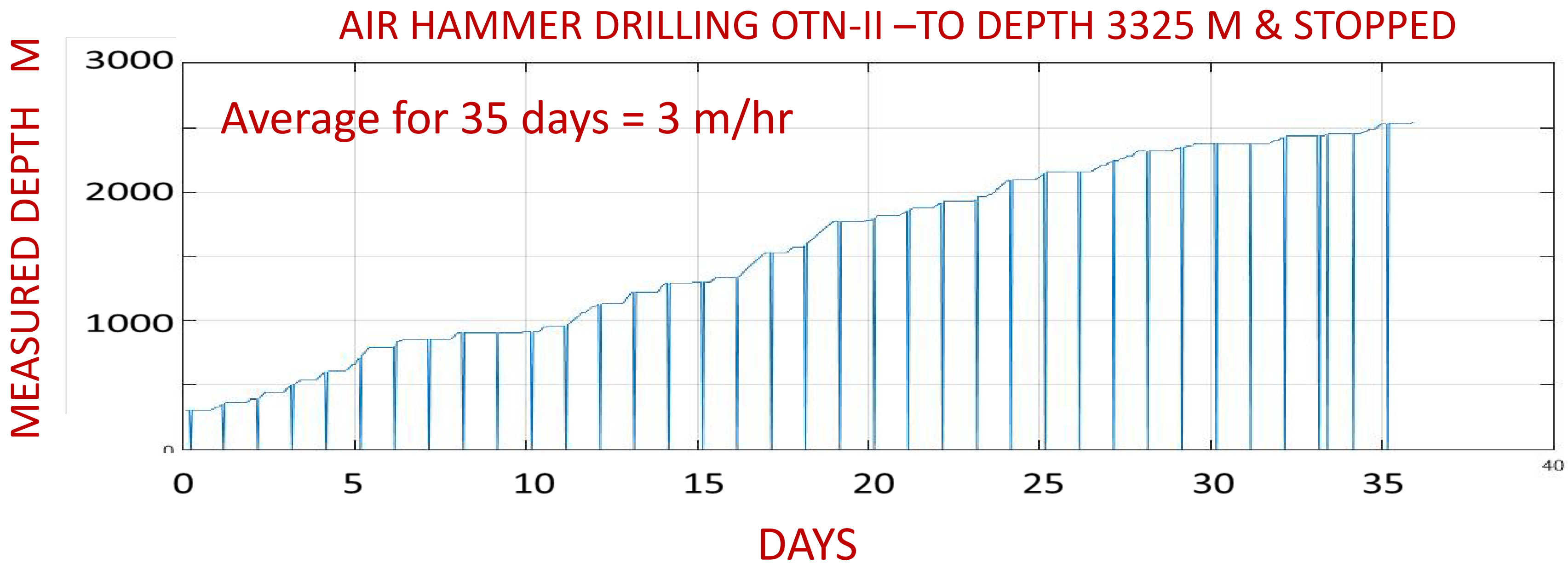
20 percussions/sec & 60 revolutions/min…

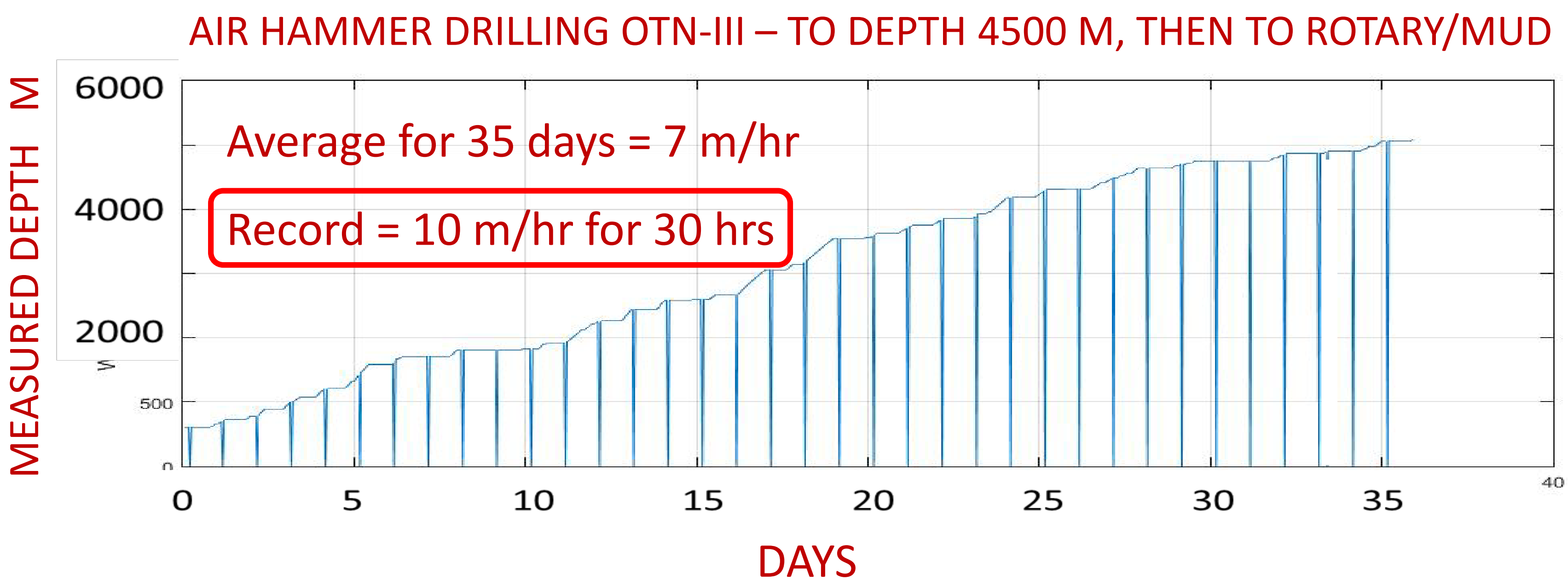
…200 – 300 bars of pressure.

Air hammer cuttings: “fingernail flakes…

…and walnut shells.”

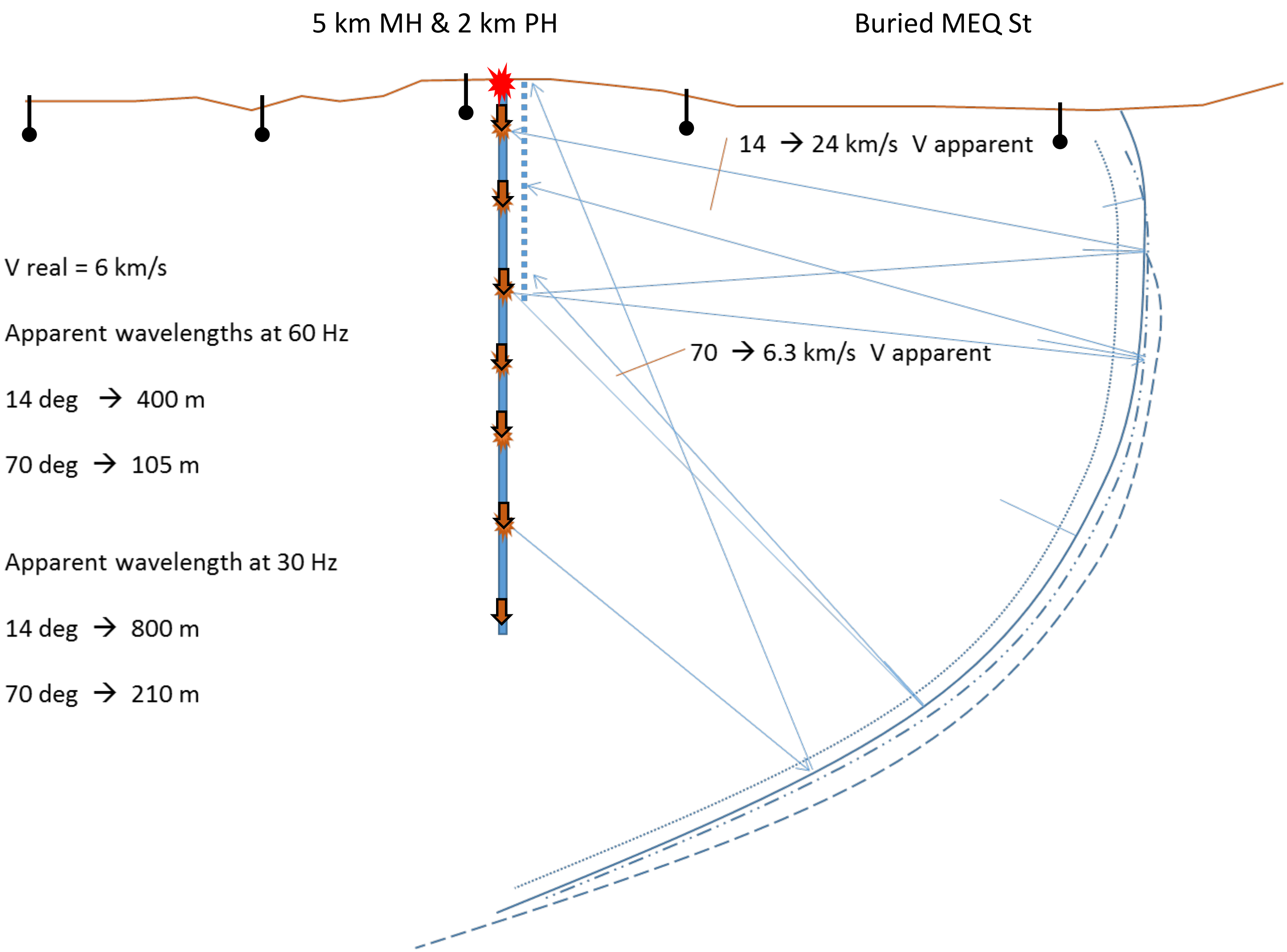





AIR HAMMER DRILLING OTN-II –TO DEPTH 3325 M & STOPPED
MEASURED DEPTH M
Average for 35 days = 3 m/hr
3000
2000
1000
0
0
5
10
15
20
25
30
35
40
DAYS


AIR HAMMER DRILLING OTN-III – TO DEPTH 4500 M, THEN TO ROTARY/MUD
MEASURED DEPTH M
Average for 35 days = 7 m/hr
Record = 10 m/hr for 30 hrs
6000
4000
2000
500
0
0
5
10
15
20
25
30
35
40
DAYS

Drill Bit Seismic imaging using MH air hammer drilling ⇩ into PH array
For 80 m sensor spacings the number of sample points per wavelength along array are:

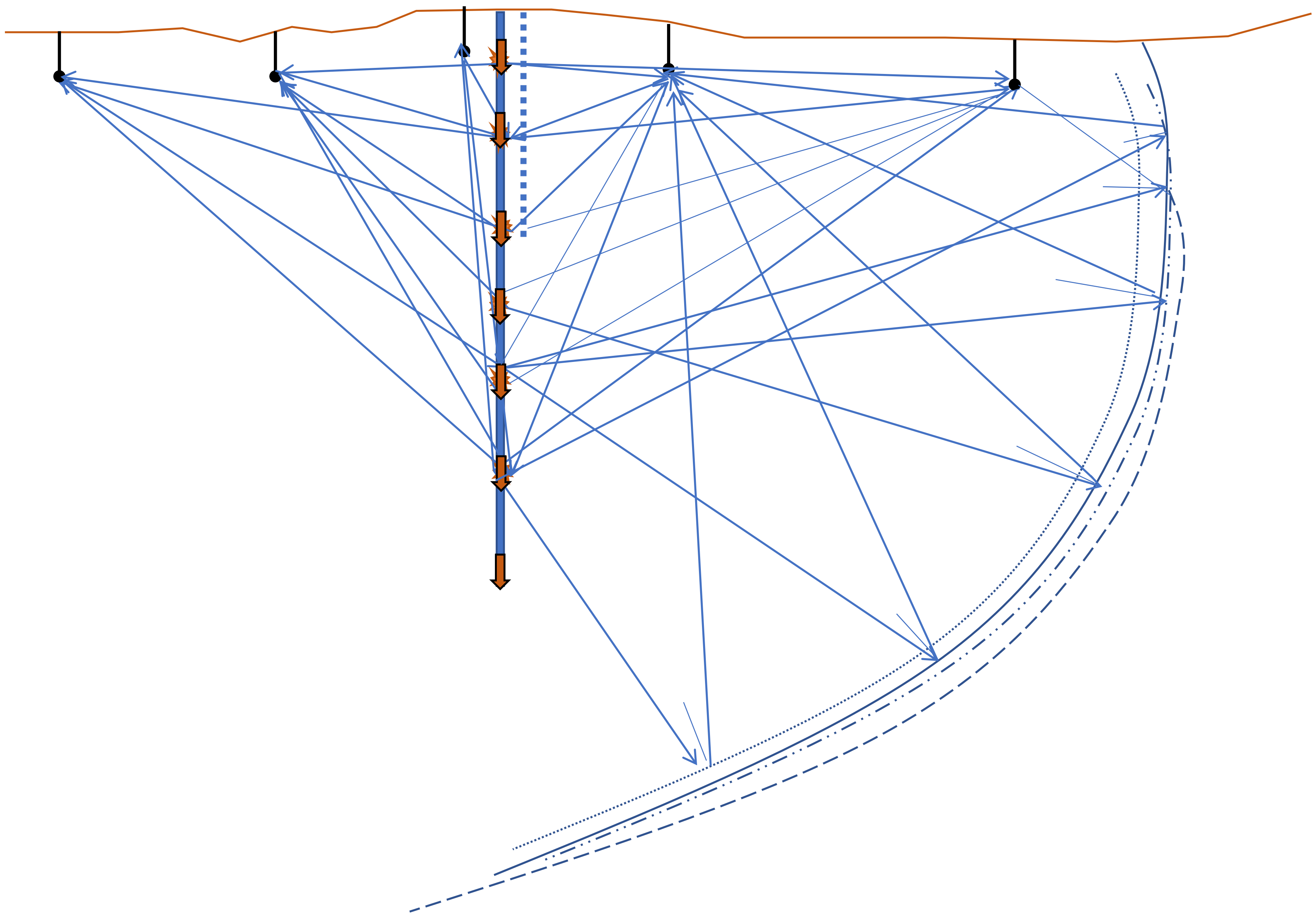
14 deg & 30 Hz → 10 excellent	resolution	→ 50 m (1/4 wave criterion)
14 deg & 60 hz → 5 very good		→ 25 m
70 deg & 30 hz → 2.4 usable?		→ 50 m
70 deg & 60 Hz → not usable		x

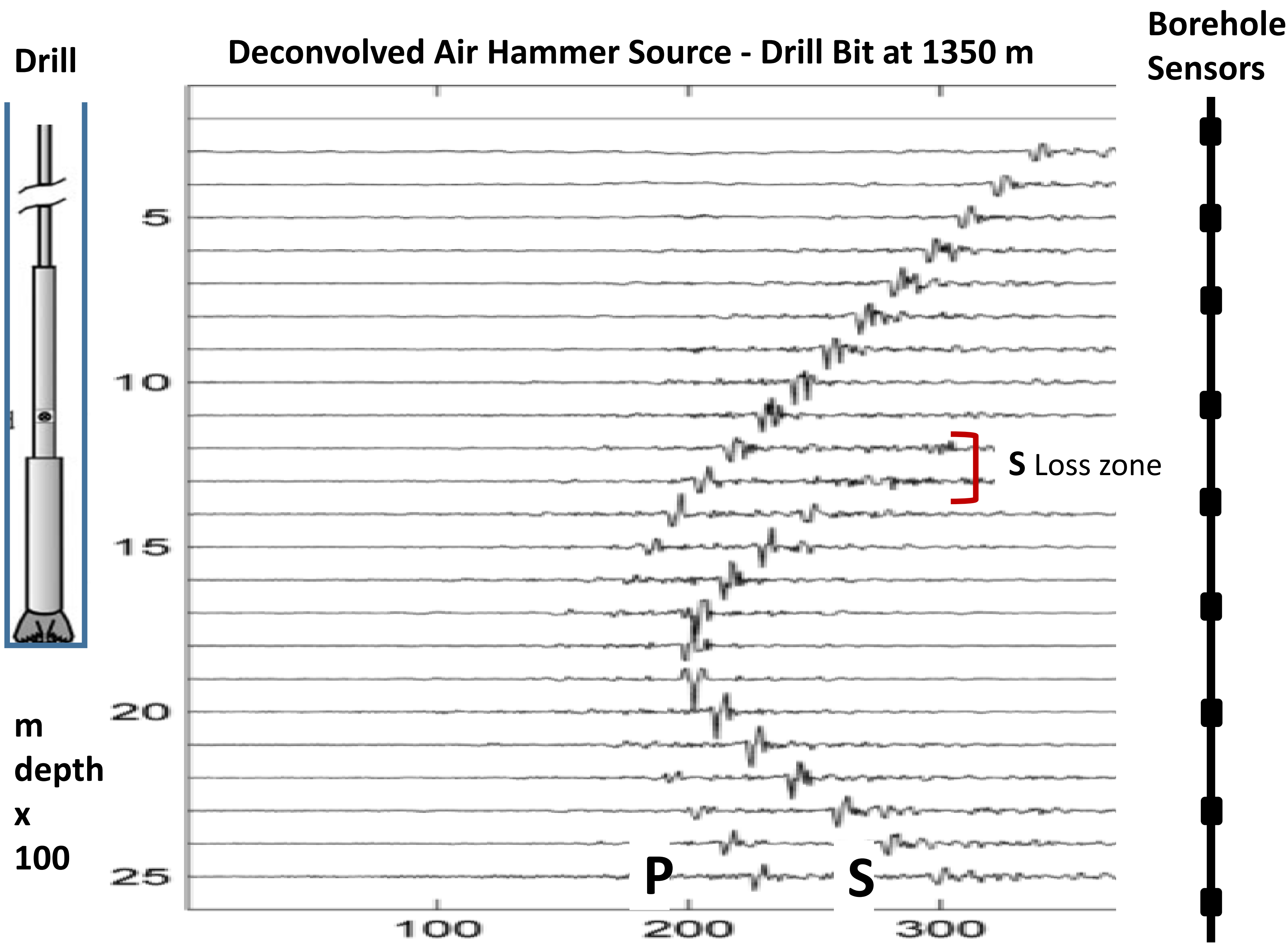


PH array with
80 m spacing

ST	Depth
24	1920
23	1840
22	1760
21	1680
20	1600
19	1520
18	1440
17	1360
16	1280
15	1200
14	1120
13	1040
12	960
11	880
10	800
9	720
8	640
7	560
6	480
5	400
4	320
3	240
2	160
1	80
	0

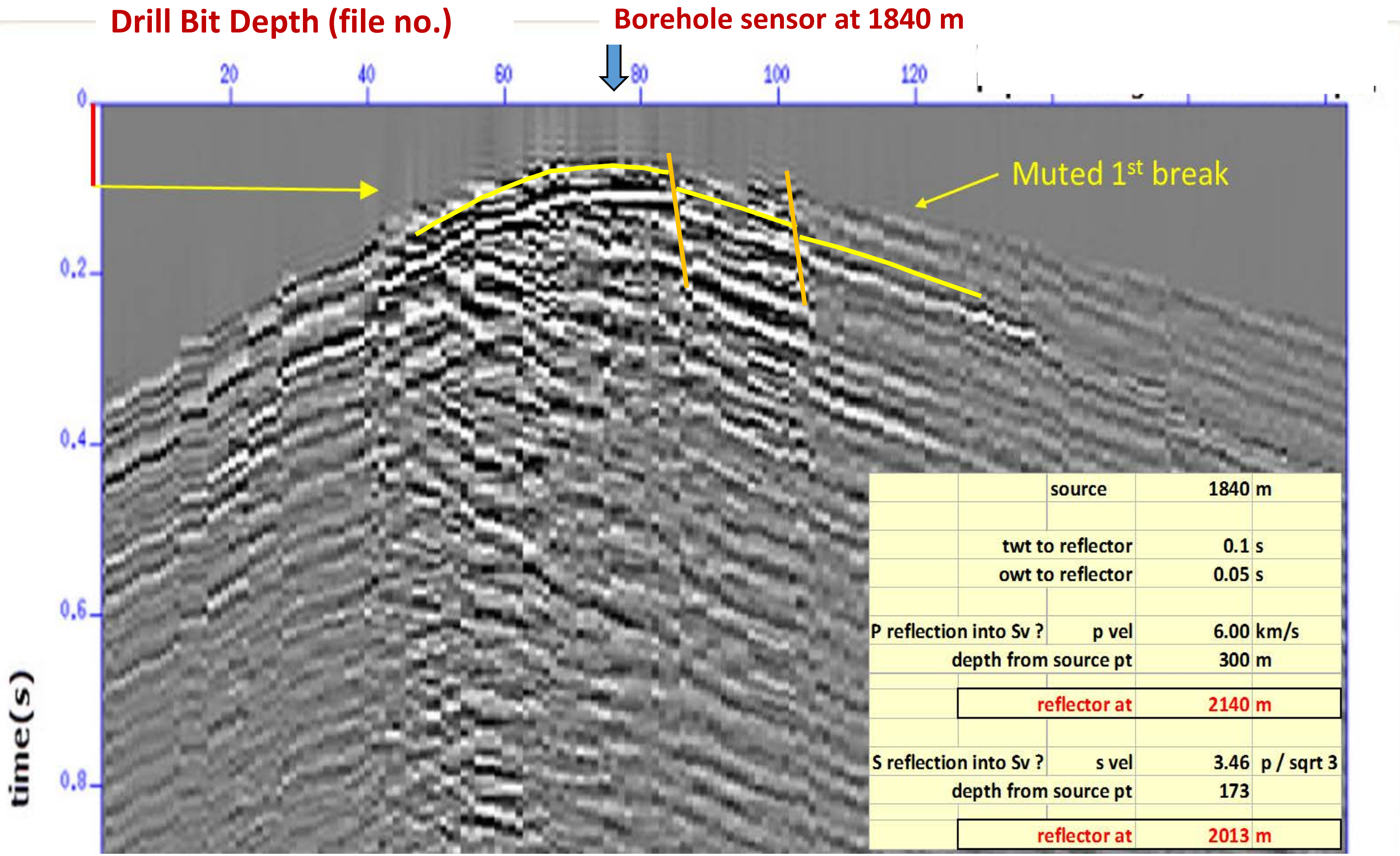
Drill Bit Seismic imaging using MH air hammer drilling into MEQ net work





Drill
Deconvolved Air Hammer Source - Drill Bit at 1350 m
Borehole Sensors
5
10
15
20
25
100
200
300
S Loss zone
P
S
m depth x 100

Faulted Reflector at ~2140 m

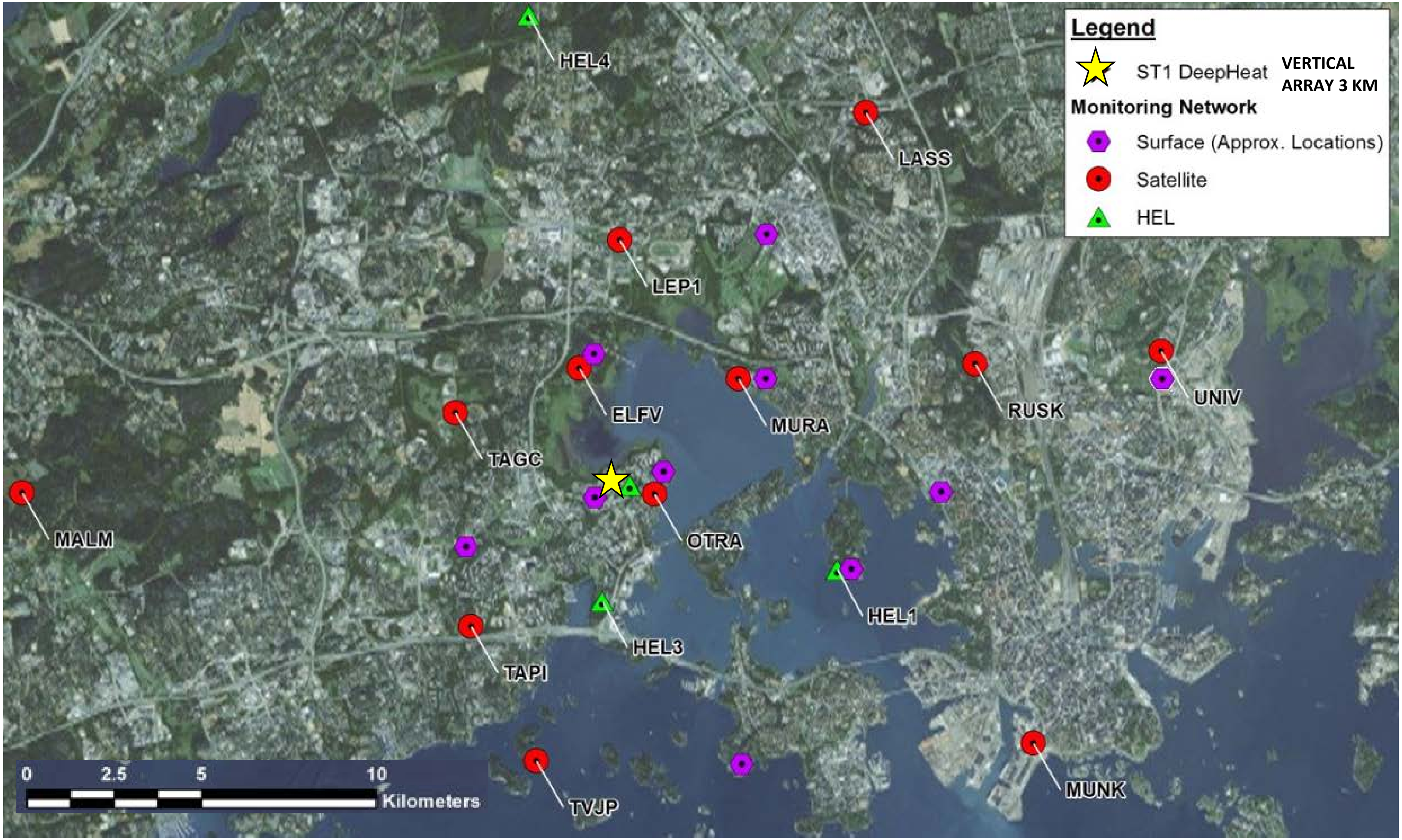


	source	1840	m
	twt to reflector	0.1	s
	owt to reflector	0.05	s
P reflection into Sv ?	p vel	6.00	km/s
	depth from source pt	300	m
	reflector at	2140	m
S reflection into Sv ?	s vel	3.46	p / sqrt 3
	depth from source pt	173	
	reflector at	2013	m

Induced Seismicity: The difference in Traffic Light Systems

Basel → 6 borehole seismic stations

Otaniemi → 12 surface; 12 borehole; 12 level VSP



st1 Otaniemi Heat Mine 3-C borehole seismic net

This diagram shows the design principles for the network and calibration shots.

The design criteria are:

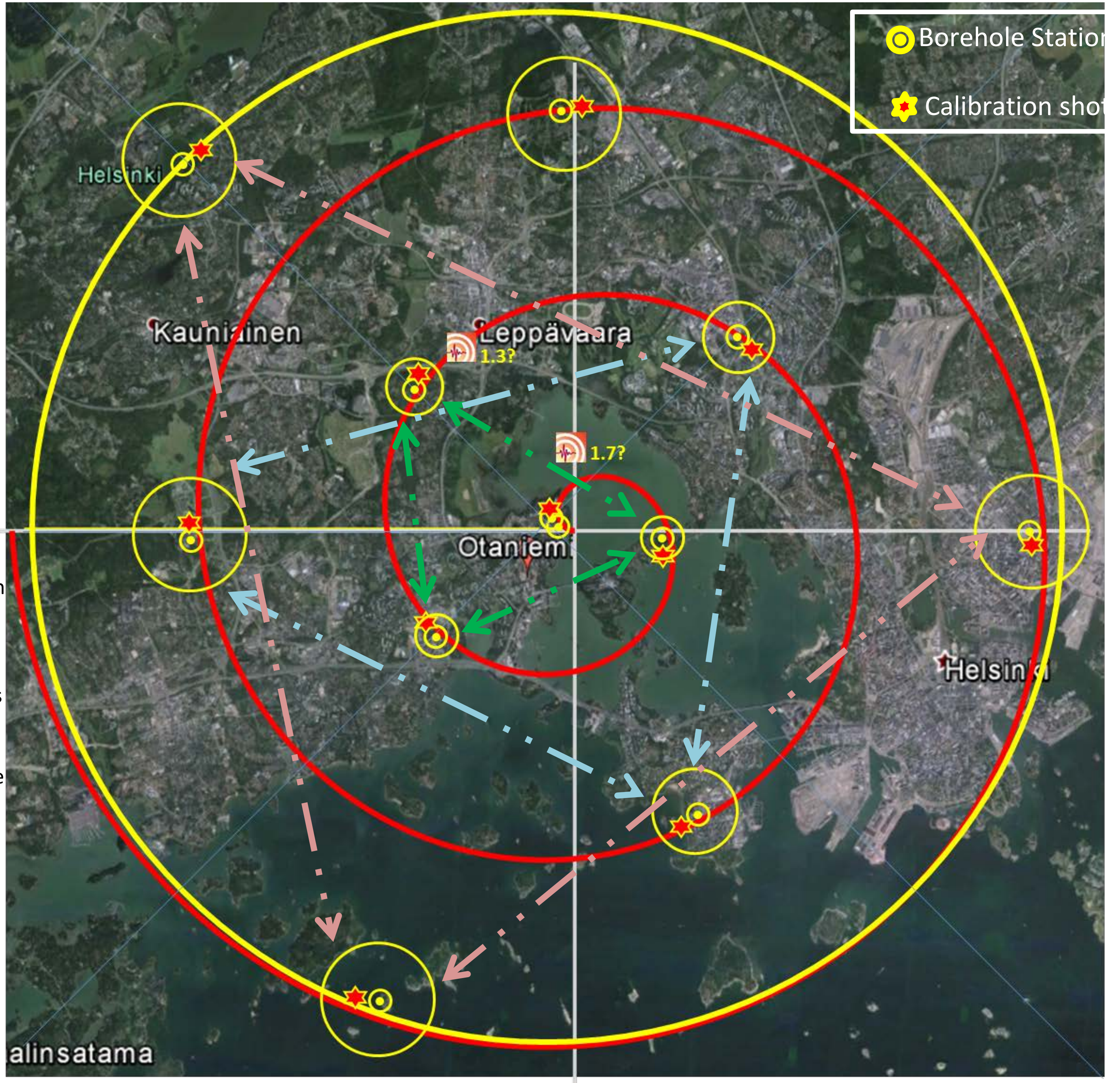
1. 3-C borehole seismometers to record both P & S for epicenter and depth control.

2. Progressive station radial distances to 1.5 times 5 km target depth for epicentral (horizontal) location control.

3. Progressive 0.2 to 0.5 km station location tolerance.

4. Triangular inner, mid, and outer ring station configuration covers azimuthal gaps.

5. Stations st01, st10 & st11 can be eliminated without significantly effecting events in NW epicenter locations.



Induced Seismicity:The difference in Traffic Light Systems

Owner	Network Name	Purpose	Locations	Details	Status
st1 Deep Heat	**Surface**	To monitor surface vibrations for the TLS	Twelve	Geophone locations and number to be confirmed. Network to be installed by Kalliotekniikka. Data to be made available to ISUH as described below.	Installed
	Satellite	To locate and estimate magnitude of seismic events for the TLS	Twelve boreholes	One geophone per borehole installed at depth between 300 and 1,200 m depth.	Existing
	Vertical	Engineering data collection to support detailed design of doublet	One borehole	12 Level MEQ VSP array installed vertically to 3 km depth.	Installed
ISUH	HEL	Temporary monitoring by ISUH	Five	Weak motion seismometers.	Existing

Notes:

1. In the event of an exceedance by the Surface network, the Satellite network will be used by st1 DH to evaluate magnitude and location of seismic events.

Stimulation plans….

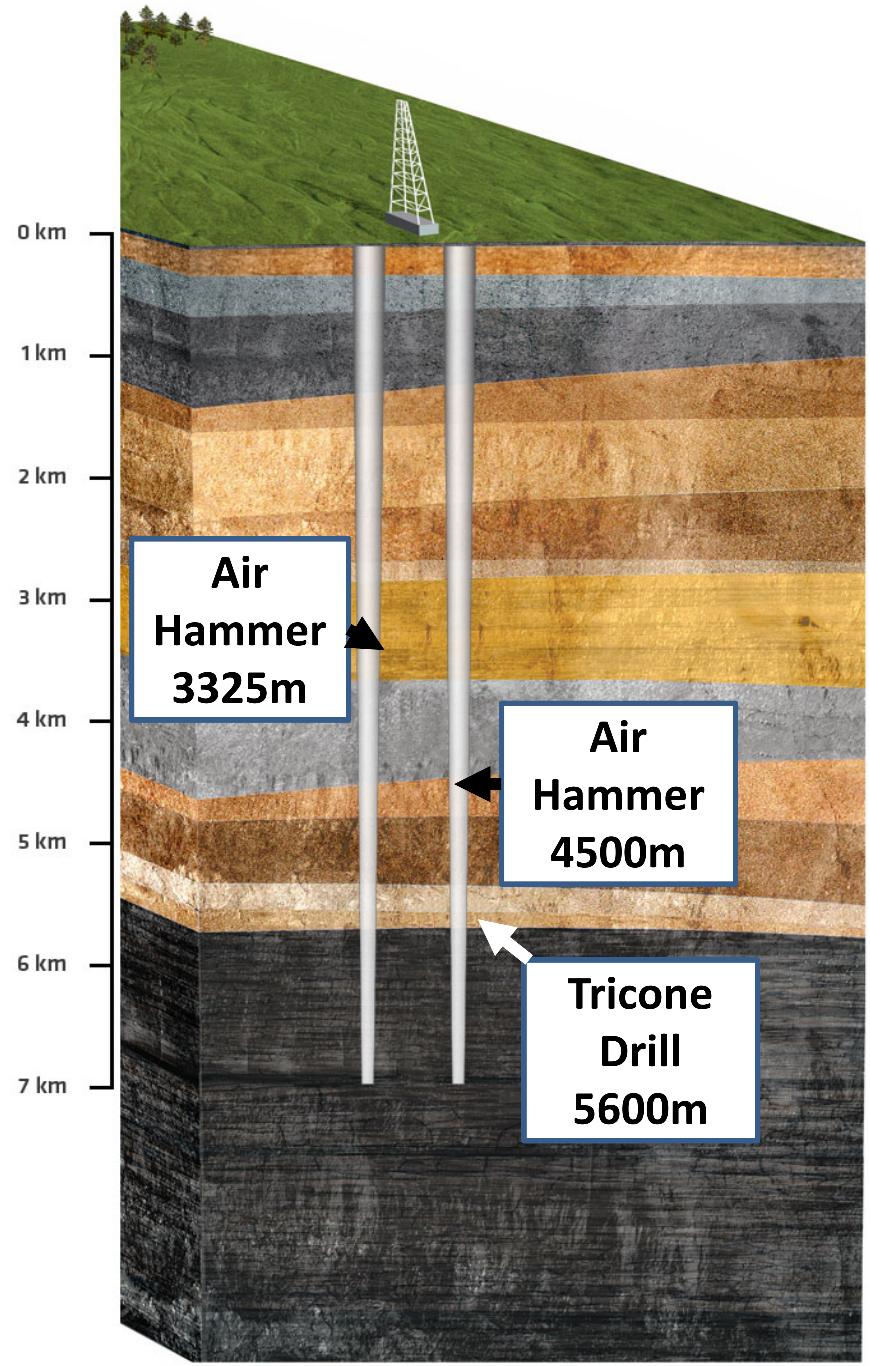
…Seismic mitigation

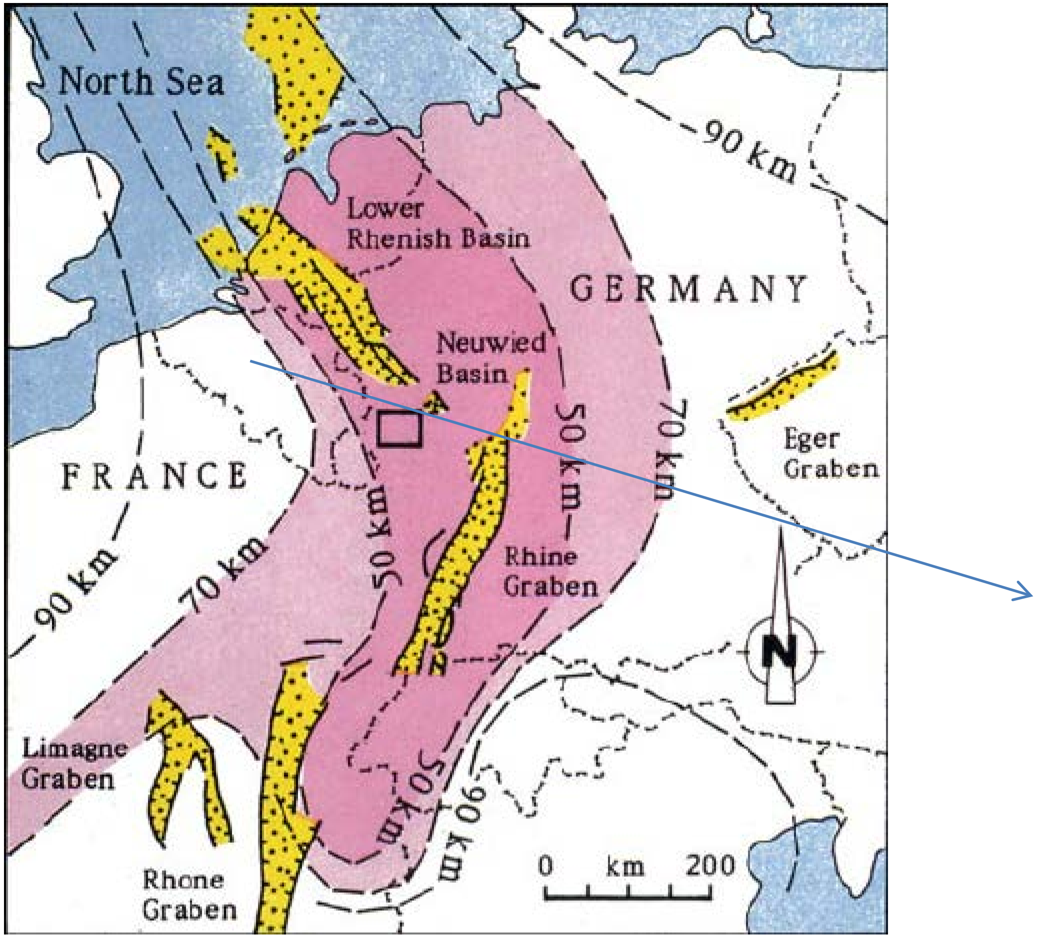
Activity	Expected	Maximum
Stimulation Duration	20 days	40 days
Daily Pumping Period	12 hours / day	24 hours / day
Post Pumping Rest Period	12 hours	12 hours
Water Volume	8,650 m^3	100,000 m^3
Injection Rate	10 L/s	30 L/s
Over pressure	400 bar	1,000 bar

CONDITIONS & ACTIONS	GREEN	AMBER	RED
PGV & Magnitude based:	PGV < 1 mm/s & M < 1.0	1 ≤ PGV < 7.5 & 1.0 ≤ M < 2.1	PGV ≥ 7.5 mm/s & M ≥ 2.1
or	or	or	or
Magnitude Only Based:	< 1.2	≥ 1.2 & < 2.7	≥ 2.7
or	or	or	or
Site Specific:	*See TLS Plan*	*See TLS Plan*	*See TLS Plan*
⇩	⇩	⇩	⇩
Actions:	Continue	Notify & Continue	**STOP** & Notify Resume only with permission

Where is the project at:

- Today, Peter Malin isn't here because he is serving on a public panel on Finnish national TV to discuss the upcoming frack (likely in March or April) and the potential for induced seismicity.
- Hole 1 was "air hammered" to 3325m, Hole 2 to 4500m.
- Tricone Drilling has proceeded on Hole 2 to 5600m
- March- Hydrofrack will be made in hole 2 at ~6000m depth, then hole 1 will be drilled to intersect fracture network




North Sea
90 km
Lower
Rhenish Basin
GERMANY
Neuwied
Basin
50 km
70 km
Eger
Graben
FRANCE
90 km
70 km
50 km
Rhine
Graben
Limagne
Graben
50 km
90 km
50 km
Rhone
Graben
0 km 200
N