



EESTI
GEOLOOGIAATEENISTUS

Seismic risk in Estonia and its impact on underground projects

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Geological Survey of Estonia



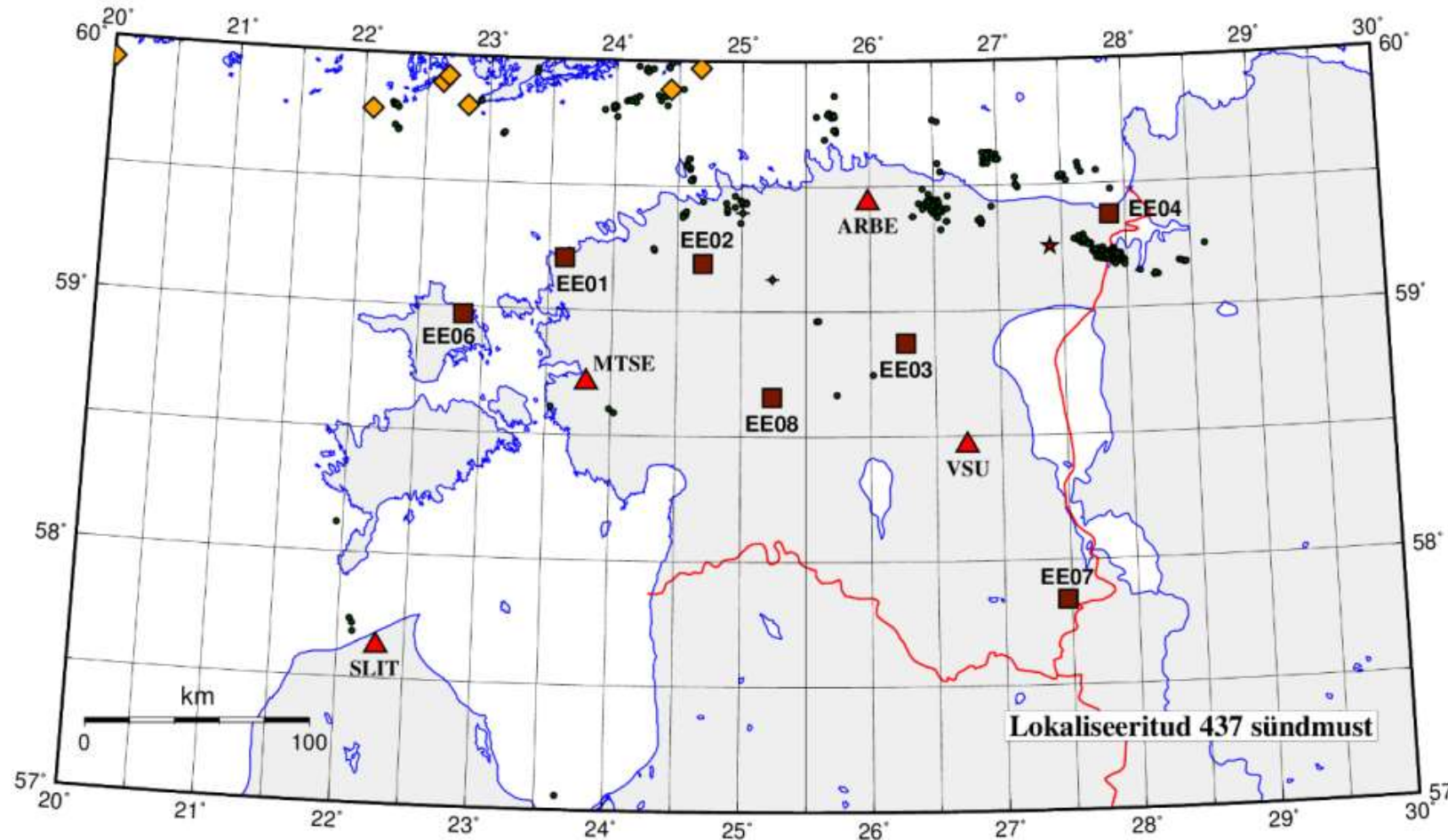
Seismic monitoring in Estonia

- One subprogramme of state environmental monitoring programme, Ministry of the Environment
- Performed by Geological Survey of Estonia
- Main international co-operation partners, also data exchange
 - **Institute of Seismology, University of Helsinki**
 - **GFZ, German Research Centre of Geosciences, Potsdam**

Seismicity in Estonia

- ~30–40 seismic events/month detected in Estonia and its surroundings
- Blasting in oil shale open mines and limestone quarries
- Military operations (e.g. sea mine eliminations)
- Magnitudes typically 1–2
- Few natural earthquakes, about one in two years, magnitudes typically 1–2
- Mine collapses

The Estonian seismic network



Red triangles:
permanent stations

Brown squares:
temporary stations

Green dots:
man-made events

Orange diamonds:
earthquakes

Red star:
mine collapse

Data from 2021

Seismic hazard and risk

- **Seismic hazard** – probability of occurrence of an earthquake in a given geographic area, within a given time window, with ground motion intensity exceeding a given threshold
- **Seismic risk** – risk of damage from earthquake to a construction; potential economic, social and environmental consequences of hazardous events that may occur in a given time period
- A well-built construction in a region of high seismic hazard is at lower risk

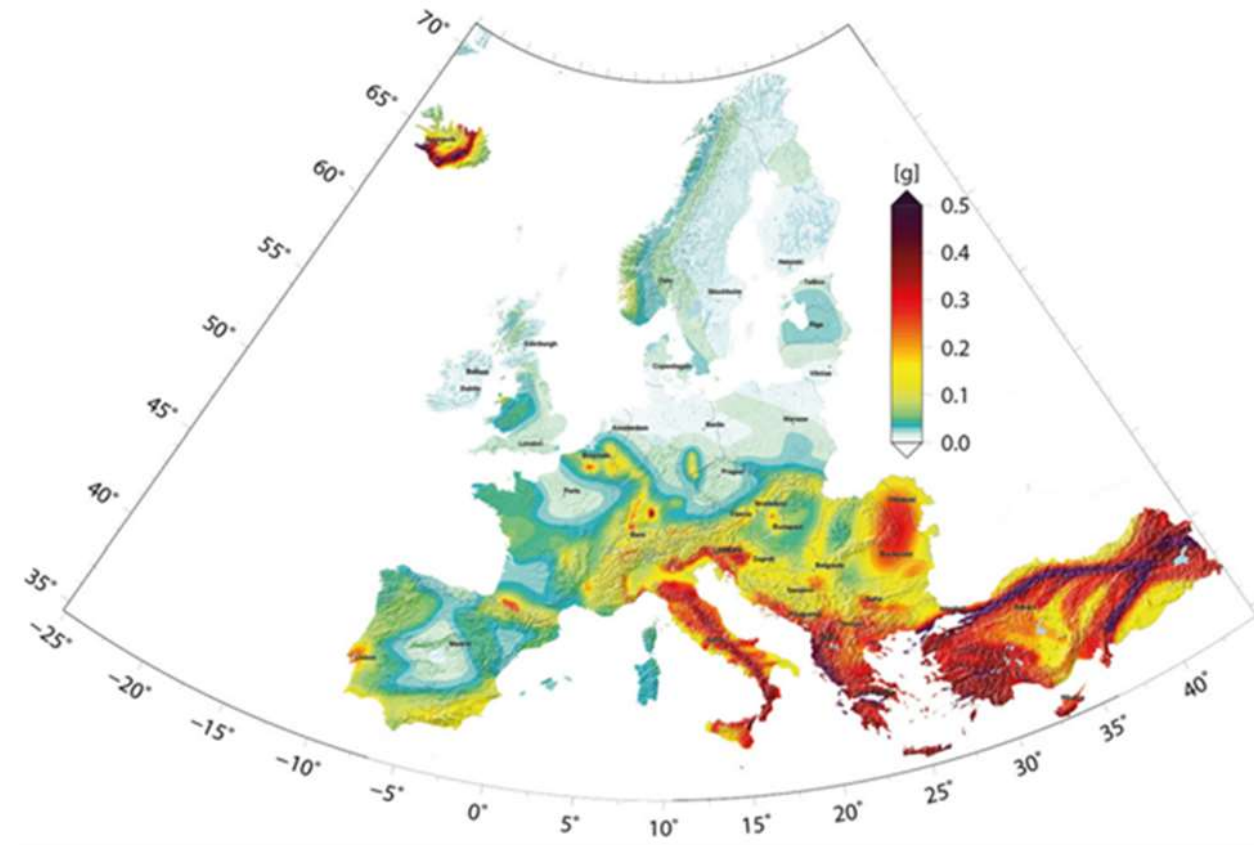
Assessing seismic hazard

- Statistical methodology

European Seismic Hazard Model 2013

Peak ground acceleration (PGA) in gravity units (g)

10% probability of exceedance in 50 yr, corresponds to PGA-values with 475 years average return period (Woessner et al. 2015)

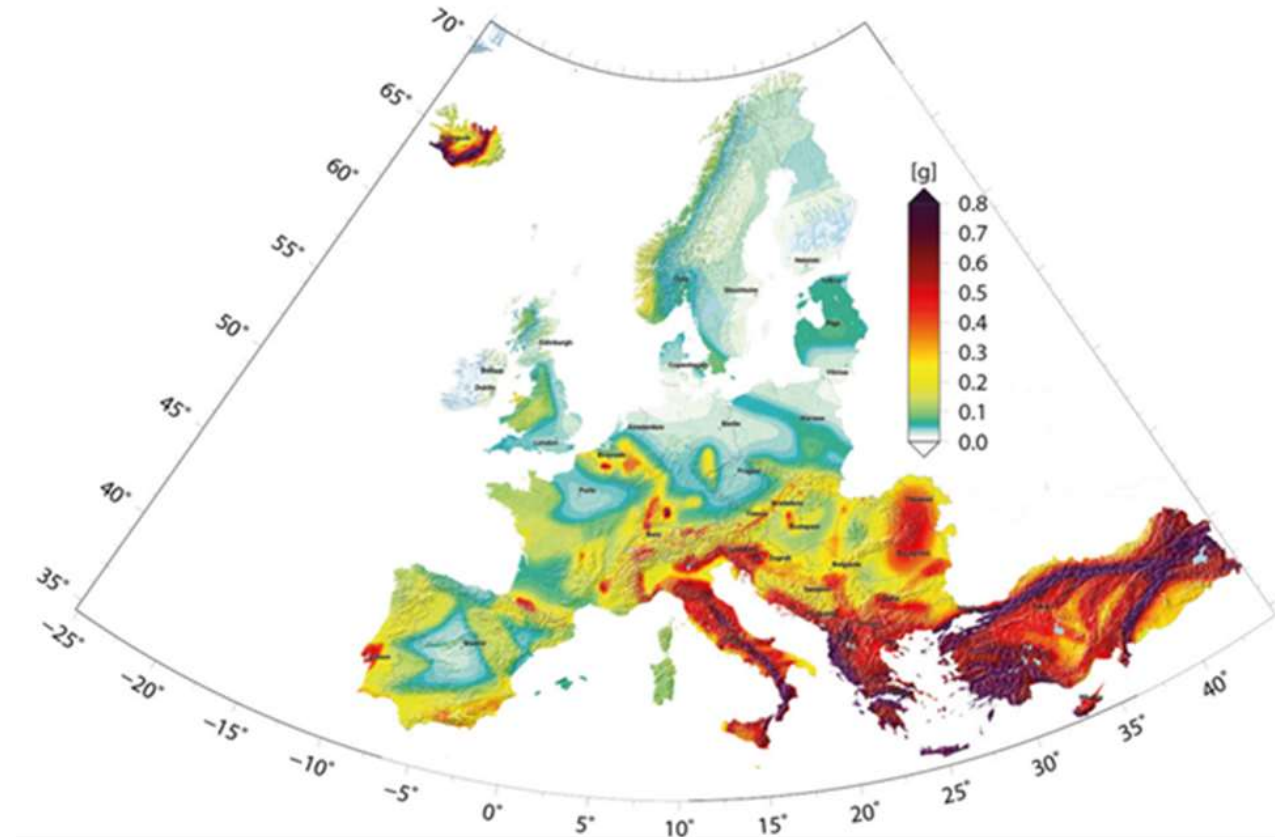


Assessing seismic hazard

- Statistical methodology

European Seismic Hazard Model 2013

Map of probabilities of PGA
exceedance of 2% in 50 years,
average return period 2475 years
(Woessner et al. 2015)

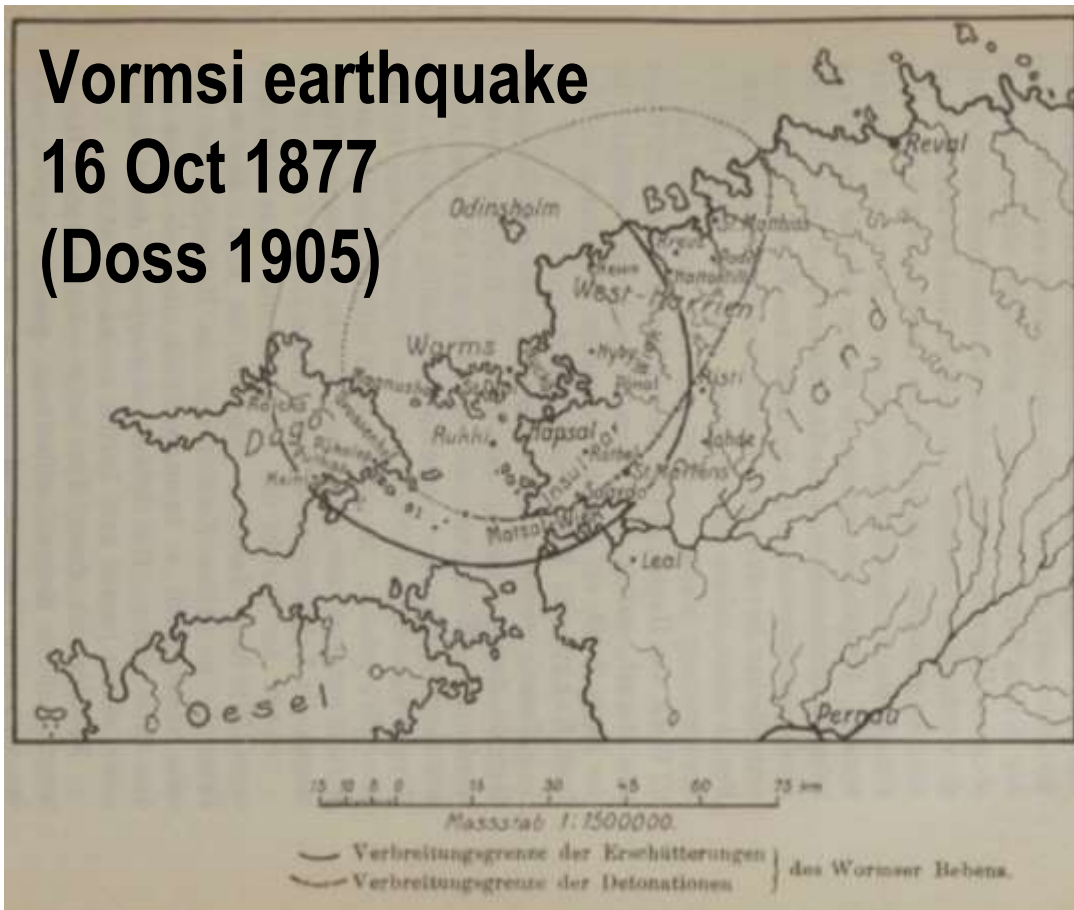


Challenges of low-seismicity areas

- A long period (centuries) of observations needed for a complete picture
- Historical data often vague, with gaps, biased
- E.g. in Estonia: short instrumental era

Data points of historical seismicity

Vormsi earthquake
16 Oct 1877
(Doss 1905)



Keri „earthquakes“ in 1912:
explosions of a minor gas deposit

19120408	1330	59.7	25.0	2.0M	III
19120408	2015	59.7	25.0	1.6M	II+
19120615?		59.7	25.0	2.0M	III+



Photo: Ivo Kruusamägi

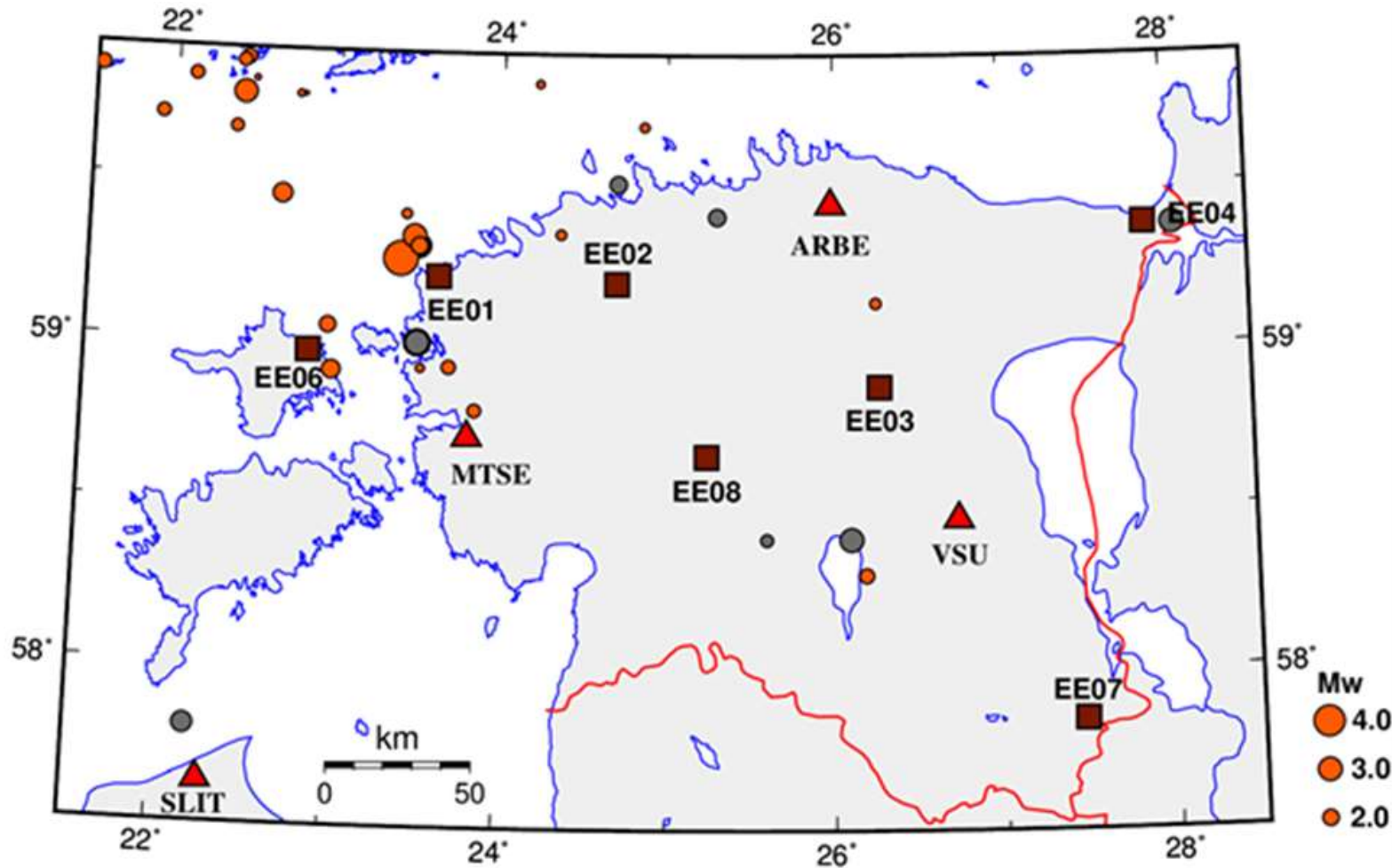
Earthquake catalogue

- Estonia and the surrounding seas

Date (UTC)				Epicentre		Depth	Magnitude	Type	Max. intensity	Notes
Year	Month	Day	Time	°N	°E	km	M _w			
1827	09	28	09	59.0	23.5	14	3.4	M	V	
1857	05	18	09	57.8	22.2	-	2.6	M	VII	
1869	02	15	00	59.5	24.7	6	2.1	M	IV	
1877	10	16	0225	59.0	23.5	10	2.6	M	IV	foreshock
1877	10	16	0225	59.0	23.5	10	3.0	M	V	main shock
1881	01	28	1215	59.37	28.05	3	3.0	M	VI	
1909	06	02	0830	58.4	25.6	7	1.5	M	III	
1931	07	12	22	59.4	25.3	5	2.1	M	IV+	

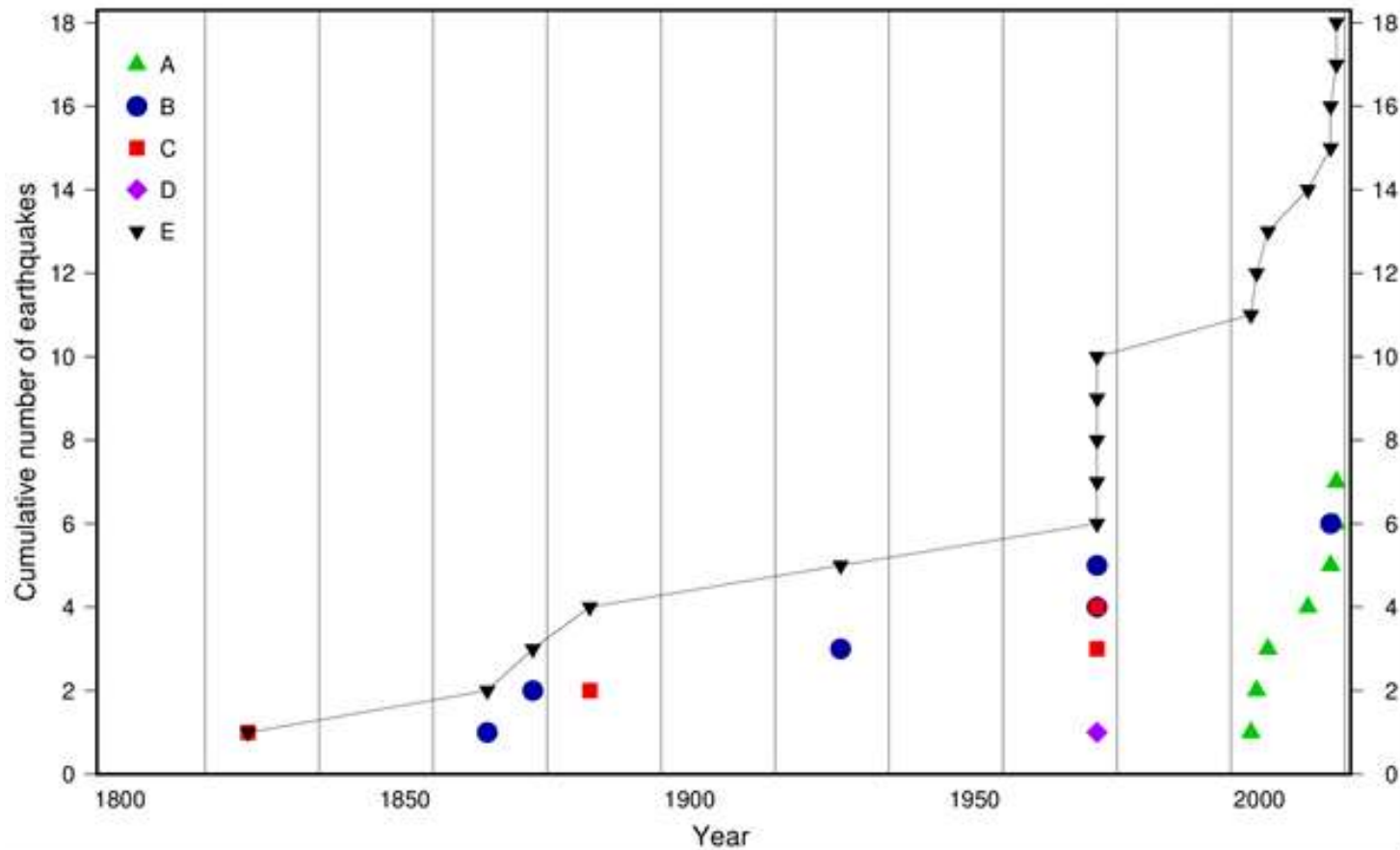
Date (UTC)				Epicentre		Depth	Magnitude	Type	Max. intensity	Notes
Year	Month	Day	Time	°N	°E	km	M _w			
1976	10	25	083945	59.26	23.39	10F	4.5	IF	VI+	main shock
1976	10	25	0849	59.3	23.5	3.5	3.0	M	IV+	aftershock
1976	10	25	0907	59.3	23.5	3.0	2.6	M	III+	aftershock
1976	11	08	101707	59.33	23.47	3.5	3.0	IF	IV+	aftershock
1976	11	22	151342	59.3	23.5	13	2.1	IF		aftershock
1980	01	09	012452	58.91	22.99	2	2.3	I		
1981	06	22	185318	59.76	22.41	-	2.9	IF	III	
1981	06	22	192737	59.45	22.66	7	2.4	IF	III	
1987	04	08	1921	58.4	26.1	7	3.0	M	IV	
1991	07	20	190435	59.83	21.53	-	1.8	I		
2003	01	12	114347	59.398	23.419	10F	1.2	I		
2004	01	28	154000	58.792	23.851	10F	1.6	IF		
2006	11	06	011140	59.677	24.857	3	1.1	I		
2013	02	04	201754	58.921	23.522	4.4	1.0	IF		
2015	11	30	191806	59.811	22.107	6F	1.6	I		
2016	05	20	012558	59.803	22.477	5F	0.6	I		
2016	11	12	024952	58.289	26.187	4F	1.8	I		
2017	03	22	030027	59.342	24.356	4F	1.2	I		
2017	07	15	080150	59.048	22.961	11.4	2.0	I		
2017	12	25	073801	59.868	22.422	2F	1.8	I		
2017	12	26	131531	59.858	22.400	2F	1.6	I		
2018	03	04	012144	58.925	23.692	3.5	1.7	IF		
2018	03	27	065029	59.690	21.914	5F	1.6	I		
2018	07	13	192003	59.807	24.215	3F	0.9	I		
2019	03	26	010228	59.653	22.367	5F	1.5	I		
2019	09	07	204735	59.760	22.750	2.1	0.8	I		main shock
2019	09	07	204901	59.761	22.781	2F	0.4	I		aftershock
2020	03	14	124401	59.132	26.254	6F	1.3	I		

Seismicity in 1827–2020



Grey dots – historical macroseismic locations
Orange dots: instrumentally located events
Dots scaled by magnitude
Current Estonian seismic network:
Red triangles – permanent stations
Brown squares – temporary stations

Cumulative seismicity – an example



A study for Paldiski

Cumulative number of earthquakes, region with max 50 km distance from Lääne-Harju municipality

Magnitude classes

A – $M_w < 2$

B – $2 \leq M_w < 3$

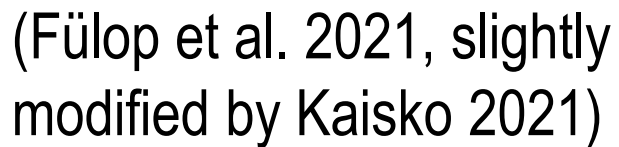
C – $3 \leq M_w < 4$

D – $4 \leq M_w$

E – all events, connected

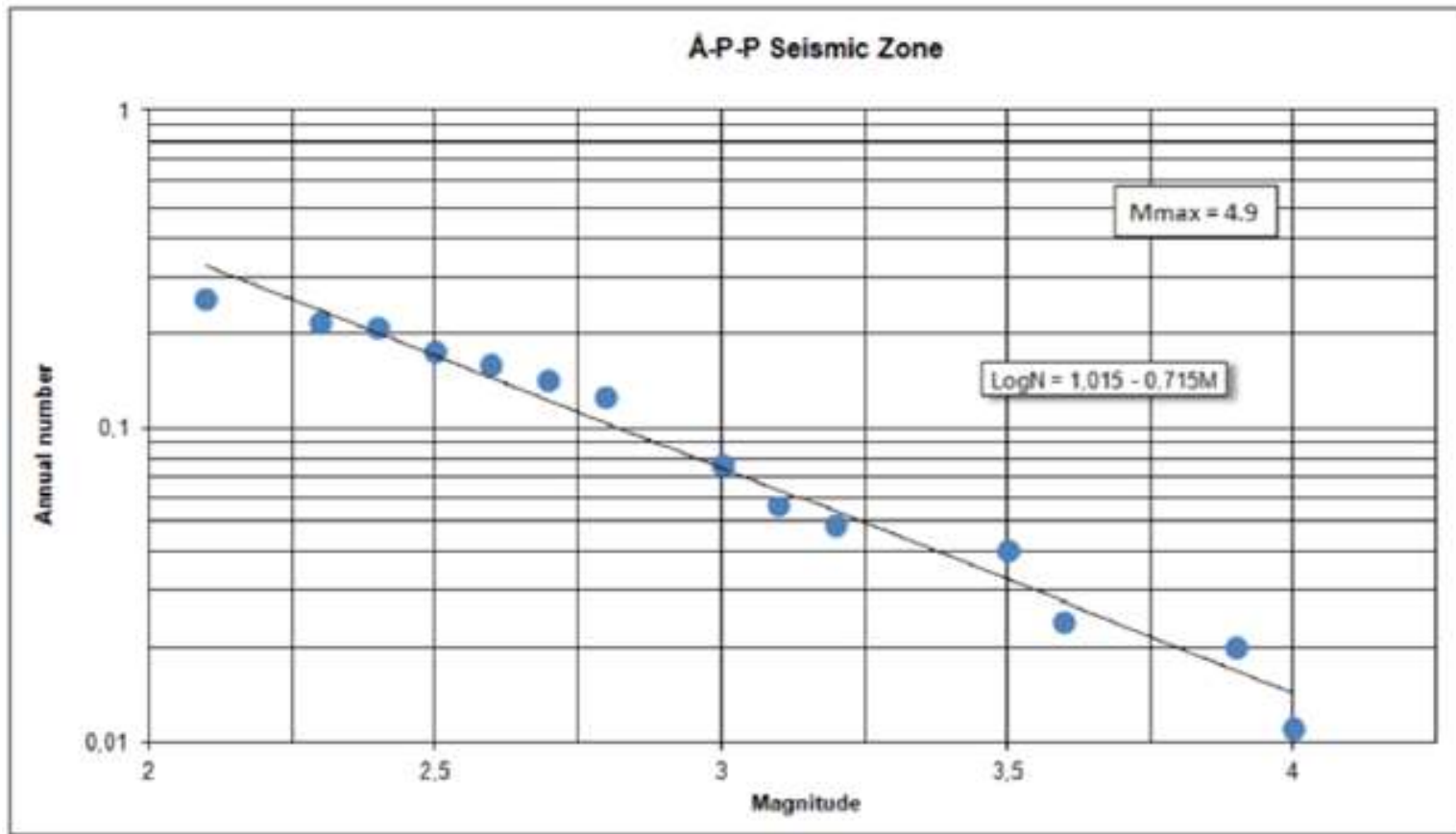
(M_w homogenized moment magnitude in FENCAT catalogue, Korja et al. 2019)

Eesti Vabariik



Black square – Pakri peninsula
Black star – Osmussaar earthquake
ÅPP - Åland-Paldiski-Pskov fracture zone

Magnitude-frequency statistics



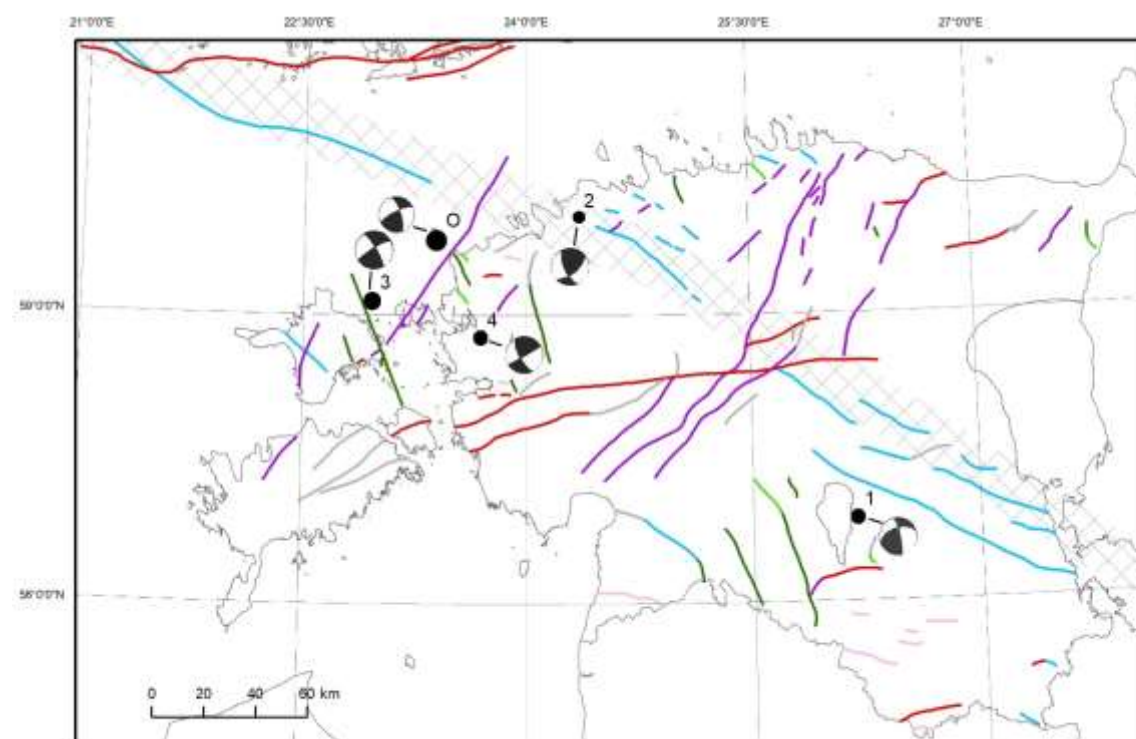
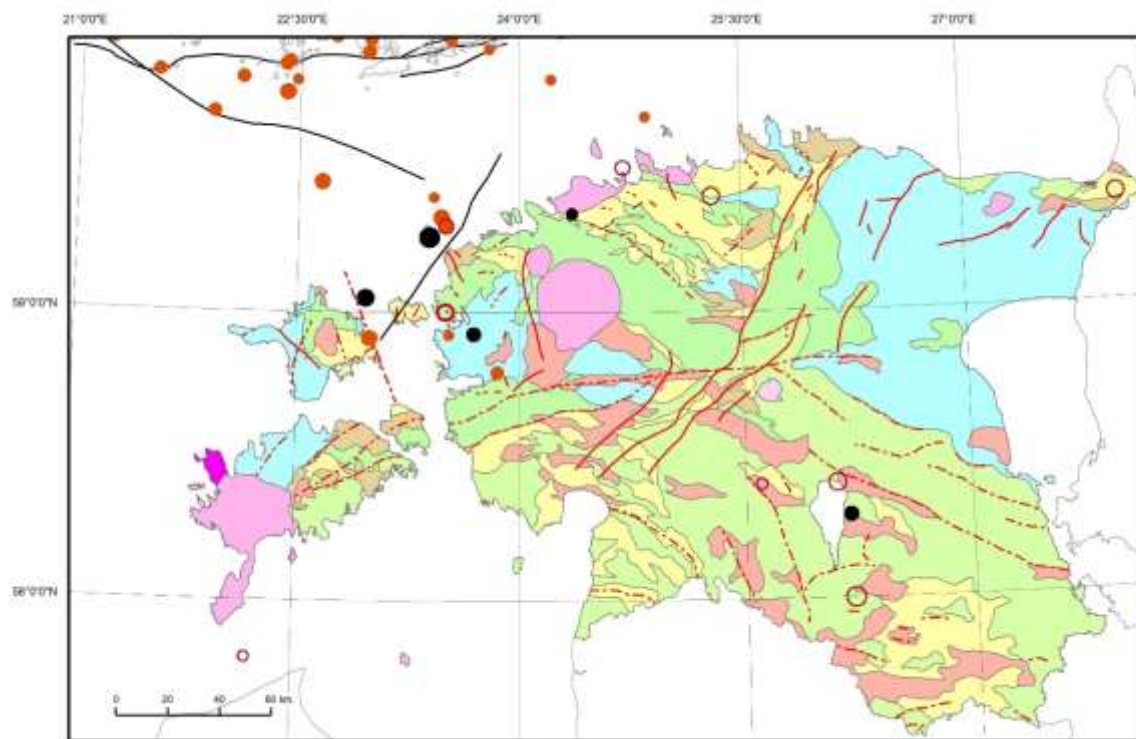
Annual magnitude-frequency curve for seismicity within the Åland-Paldiski-Pskov zone (Saari 2012)

Gutenberg-Richter formula adjusted for local conditions:
 $\log N = 1.015 - 0.715M$

M – magnitude

N – number of events $\geq M$

Geological context of recent earthquakes



(Soosalu et al. 2022)

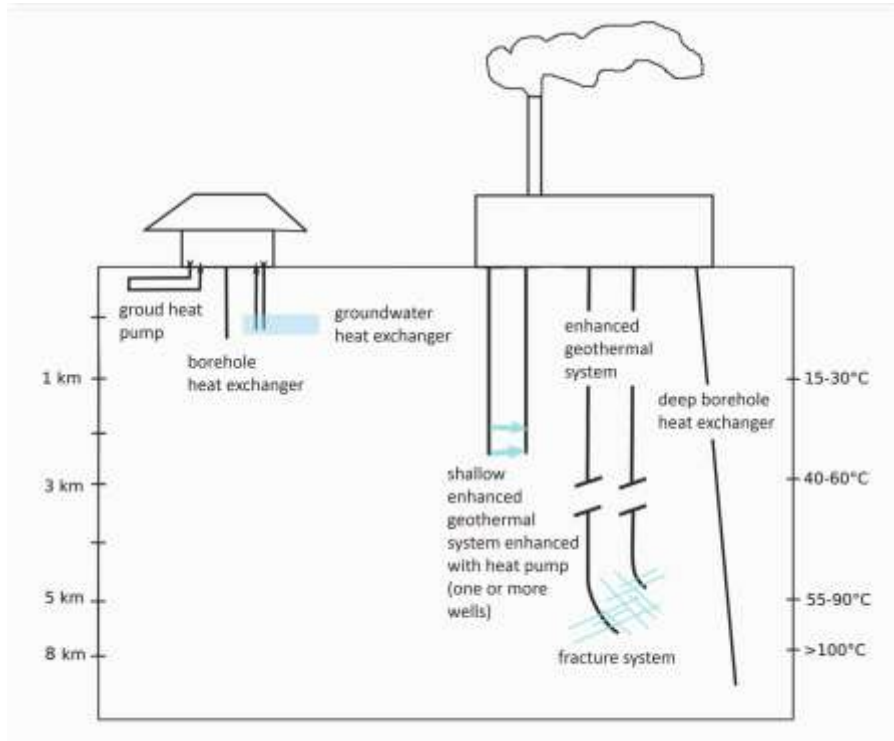
Aspects of seismic risk

- Risk due to **natural earthquakes**
- Risk due to **human activities**, e.g. mining, fracking for deep geothermal wells
- Underground constructions and **possibility for induced seismicity**
- **Social acceptability of activities/constructions causing earth tremors**

Project SEISMIC RISK of Finland

- University of Helsinki, VTT Technical Research Centre, GTK
- Stakeholders: Academy of Finland (funding), Ministries of Environment and Economic Affairs and Employment, Radiation Nuclear Safety Authority (STUK), Cities of Helsinki, Espoo and Vantaa, Centre for Economic Development, Transport and the Environment, several energy companies operating in Finland
- **Geological Survey of Estonia – international co-operator**

Motivation of project SEISMIC RISK



(Uski & Piipponen 2020)

- Deep geothermal energy systems may induce earthquakes – seismic risk to critical sensitive infrastructure
- Mitigation with transparent regulatory processes, seismic monitoring plans, regional planning
- Focus: evaluating, mitigating and communicating seismic hazard and risk in an urban environment
- Challenges: unclear regulatory process, unclear roles of different actors, adequate information to authorities

Benefit for Estonia

- Assesses potential of geothermal systems to induce earthquakes, associated risks
- Induced earthquakes: previously non-existing seismic hazard in urban regions, may exceed natural seismic hazard and impact sensitive infrastructures and operations
- General scheme for separating seismic hazard related to induced/natural seismicity
- Highlights gaps in governing geothermal energy processes, sustainable and societally acceptable development

Less need to reinvent the wheel here

- Open Access seismic hazard maps of Finland – region of Estonia included
- Ground-motion prediction equations (GMPE) for magnitudes > 2 for Finnish basement – analogous with Estonian basement
- New guidelines on construction of critical infrastructure, case studies from Helsinki-Espoo area
- Educational material for governmental/municipal decision makers, politicians and general public on seismic hazard, seismic risk and induced seismicity

Aspects of seismic risk

- Risk due to natural earthquakes
- Risk due to human activities
- Possibility of induced seismicity due to underground constructions
- Social acceptability of activities/constructions causing earth tremors

