Lessons learned from the seismic hazard assessment of NPPs in Switzerland

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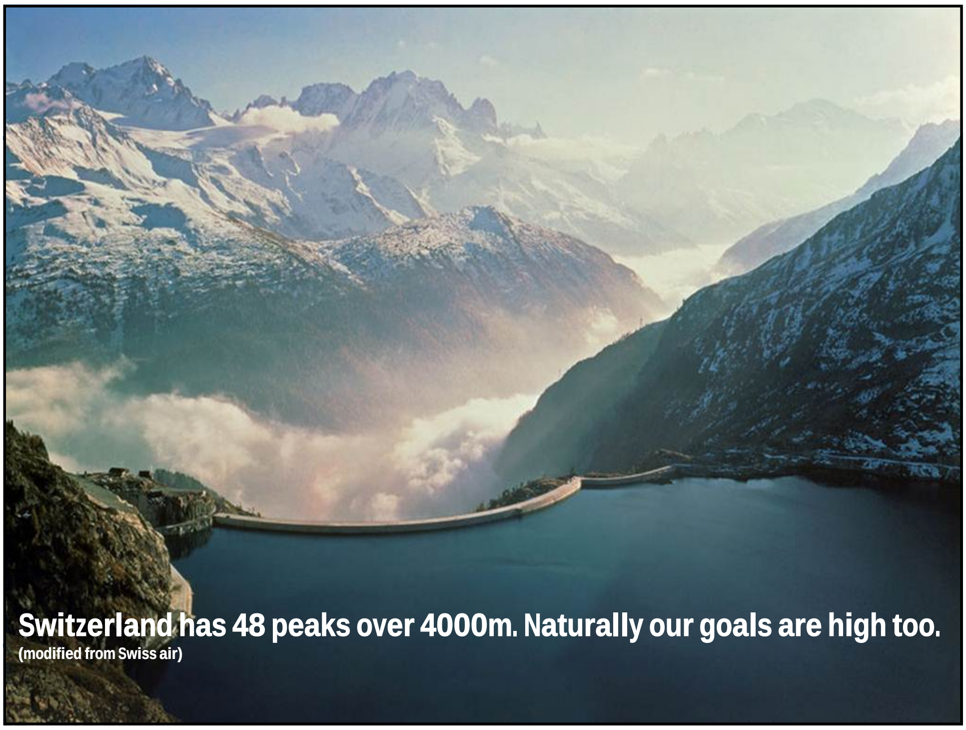

Outline

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- **Introduction and Background of the Project**
- **Project Structure and Organization**
- **Subproject Tasks and Achievements**
- **Challenges and Lessons Learned**
- **Some Conclusions**

Introduction
Tectonic conditions of Switzerland

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- **Switzerland is not really a SCR, but rather an ASCR**

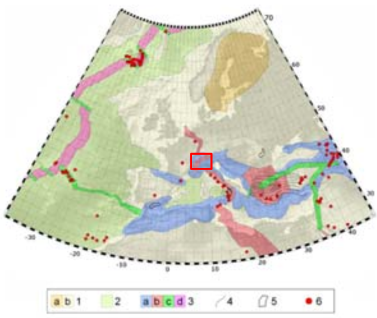

Fig. 2 Seismotectonic map of the Euro-Mediterranean area developed for the SHARE project by WP3.2. *1* SCR, shield (*a*) and continental crust (*b*); *2* oceanic crust; *3* ASCR, compression-dominated areas (*a*) including thrust or reverse faulting, associated transcurrent faulting (e.g., tear faults), and contractional structures in the upper plate of subduction zones (e.g., accretionary wedges), extension-dominated areas (*b*) including associated transcurrent faulting, major strike-slip faults and transforms (*c*), and mid oceanic ridges (*d*); *4* subduction zones shown by contours at 50-km-depth interval of the dipping slab; *5* areas of deep-focus non-subduction earthquakes; *6* active volcanoes and other thermal/magmatic features

From: Delavaud, E. ; Cotton, F. ; Akkar, S. ; Scherbaum, F. ; Danciu, L. ; Beauval, C. ; Drouet, S. ; Douglas, J. ; Basili, R. ; Abdullah, M. ; Sandikkaya, M. ; Segou, M. ; Faccioli, E. ; Theodoulidis, N.: Toward a Ground-Motion Logic Tree for Probabilistic Seismic Hazard Assessment in Europe. In: Journal of Seismology 16 (2012), February, 22, p. 451{473.

Introduction
Nuclear facilities in Switzerland

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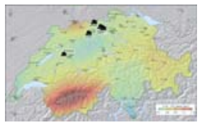
- KKW Beznau (PWR, 2x365 MW, 1969,71)
- KKW Mühleberg (BWR, 373 MW, 1972)
- KKW Gösgen (PWR, 970 MW, 1979)
- KKW Leibstadt (BWR, 1165 MW, 1984)
- △ ZWILAG (Interim dry storage, 2001)
- ▲ Grimsel Rock Laboratory (Granite)
- ▲ Mont Terri Rock Laboratory (Clay)

plus 3 small research reactors
(at the Universities of Basel & Lausanne,
as well as at the Paul Scherrer Institute, PSI)



Introduction
History of PEGASOS and PRP

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1990-1997	Federal Nuclear Safety Inspectorate (HSK) identified the need to update the seismic hazard assessments for Swiss NPPs, as not compliant any more with the state-of-the-art (with regard to progress in the US)
Dec. 1998	Swiss regulator started development of „PSHA Guidelines“ - Based on modern US recommendations
June 1999	Swiss regulator requested Swiss NPP operators to perform a new PSHA that complies with SSHAC Level 4
March 2000	NPP operators submitted first draft project plan: „Probabilistische Erdbebengefährdungsanalyse für die KKW-Standorte in der Schweiz“ (PEGASOS)
2001-2004	**Project realization – Duration: 4 years** - **Project lead NAGRA** - **Participatory peer review by HSK**
Nov. 2004	PEGASOS review meeting: Specialists meeting, Baden
2004-2006	Review by the utilities and performance of several additional studies
2007	Planning of a refinement study: PEGASOS Refinement
2008-2013	**Realization of the PEGASOS Refinement Project (PRP) – Duration: 4.5 years** - **Project lead swissnuclear** - **Participatory peer review by ENSI (formerly HSK)**

Project Structure and Organization

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Project Structure – Subprojects (SP)

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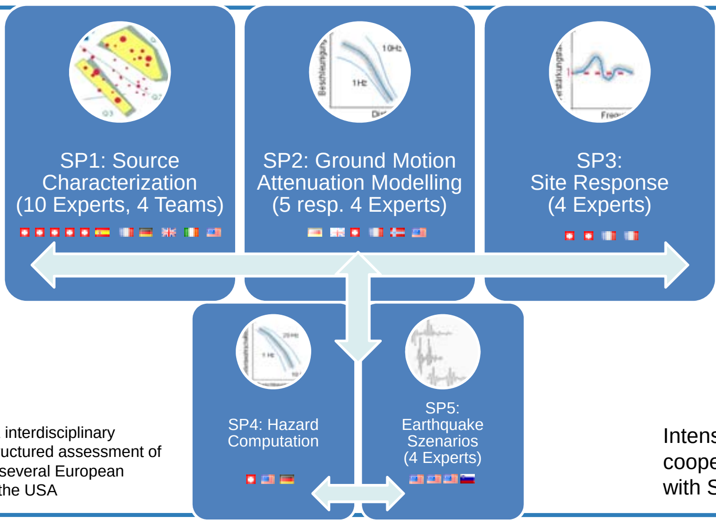

International & interdisciplinary project with structured assessment of 25 experts of several European countries and the USA

Intensive cooperation with SED

PEGASOS vs. PEGASOS Refinement
Areas of Improvement

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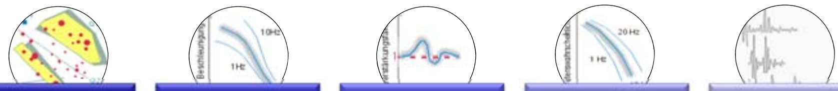

SP1 – Source Characterization	SP2 – Attenuation Models	SP3 – Site Effects	SP4 – Hazard Computations	SP5 – EQ Szenarios
• New earthquake catalog ECOS09	• **Complete revision** • New attenuation equations • New unified logic tree	• New site specific investigations • Re-revaluation of site amplification	• Full recomputation • More (sensitivity) calcualtions	• **New**

Workload / Modifications

Project Organigram

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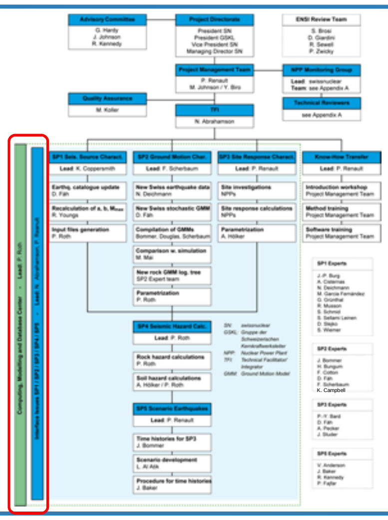

Schedule and Cost Overview

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SSHAC Workshops: 25 (initally planned were 12 WS)

Working Meetings: 16
Numerous webmeetings and individual sessions: >20

Total costs for PEGASOS & PRP

	Year	Cost*
PEGASOS	2000 – 2004	~10‘510‘000 CHF
Results evaluation	2005 – Mid 2008	~725‘000 CHF
PRP	End 2008 – 2013	~8‘400‘000 CHF
PRP – NPP site investig. & amp.func. computation	2008 – 2010 2011 & 2013	~8’135‘000 CHF

* excl. ENSI charges

Subproject Tasks and Achievements

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Seismic Source Characterization (SP1)

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- **Four different source models with alternative submodels**
- **New earthquake catalog of Switzerland (2011), to ensure the compatibility of the PRP results with the new generation of seismic hazard assessments for Switzerland**
- SED used new magnitude conversion/scaling relationship
- This showed to have meaningful effect on the hazard results in reducing the mean ground motions and especially at low annual probabilities of exceedance
- Hazard sensitivity for SP1: Mmax distributions of the source zones are the most important parameter controlling the hazard results

Seismic Source Characterization (SP1) Data collection

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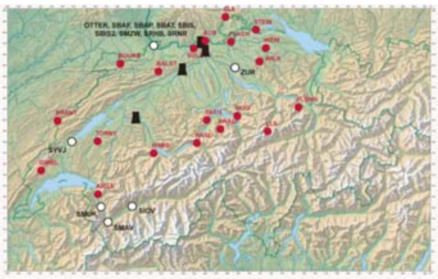
- **Site characterziation of 20 (34) stations of the Swiss network**
- **Compilation of a comprehensive database with all station and site information**



Ground Motion Characterization (SP2)

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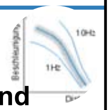

- **Identified in PEGASOS as part with the largest uncertainty**
- **Key issue is to constrain the best estimates of median ground motions in Switzerland, with their associated variability and the range of epistemic uncertainty**
- **Avoid double counting and/or missing variability & uncertainty:**
  - Aleatory variability
    - SP2 rock → Single station sigma
    - *SP3 soil → Site amplification*
  - Epistemic uncertainty
    - SP2 rock → Alternative GMPEs (median and sigma)
    - *SP3 soil → Alternative site profiles and site response methods*

Ground Motion Characterization (SP2)

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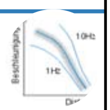

Key contributions of SP2:

- **Consensus selection of GMPEs applicable for Switzerland**
  - Development of a new Swiss stochastic model
- **Adjustment of GMPEs to small magnitude data in Switzerland**
- **Host-to-target correction for Switzerland ("Vs-kappa")**
  - Correction to NPP specific rock conditions
- **Aleatory variability model ("Single Station Sigma")**
  - Joint effort of PRP and NGA (PEER)
- **Maximum ground motion model**
- **Testing of GMPEs against intensity data and Swiss dataset**
- **V/H models for hard rock**

Ground Motion Characterization (SP2)
Selected GMPEs

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GMPE	Region
Abrahamson & Silva (2008)	Western North America (NGA)
Boore & Atkinson (2008)	
Campbell & Bozorgnia (2008)	
Chiou & Youngs (2008)	
~~Atkinson & Boore (2006)~~	~~Eastern North America~~
~~Toro (1997,2002)~~	
Akkar & Bommer (2010 + HF extension)	Europe, Mediterran & Middle East
Akkar & Cagnan (2010)	
Bindi et al. (2011)	
Zhao et al. (2006)	Japan
Edwards et al. (2011) - Stochastic Model	Switzerland

But: none of the models was used “as published” and had adjustments

Site Response Characterization (SP3)

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- **Extensive site investigations and measurement campaigns were performed to collect more data**
  - The site investigations, with multiple techniques, revealed a larger scatter in the data than before, which lead to various interpretation possibilities and to an increased model variability
- **Site-specific definition of rock for each NPP based on Vs-profile and $V_{S,30}$ for the rock ground motion models**
- **Clear separation of aleatory and epistemic variability between SP2 and SP3 in order to avoid double counting**
- Hazard sensitivity for SP3 identified the choice of Vs-profiles, material parameters and the weighting between the EQL and NL methods as the key parameters

Earthquake Scenario Development (SP5)

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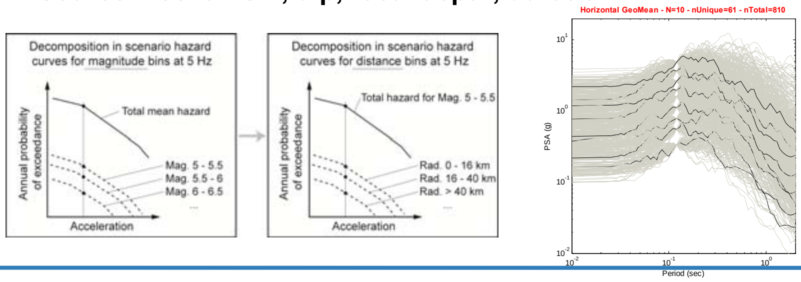
Based on final deaggregation:

- ➢ **Breaking down total hazard into scenario hazard curves**
- ➢ **Development of conditional (mean) response spectra**
- ➢ **Development of consistent time histories for struct. analyses**
- ➢ **Attribution of: Location of controlling earthquake, magnitude, source mechanism, dip, focal depth, duration**



Various Challenges & Leassons Learned

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PEGASOS vs. PRP, Model Complexity

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Number of logic tree branches:

SP1*: Source	PEGASOS	PRP	SP2: GM	PEGASOS	PRP⁺
EG1a	219	219	ALL	533	
EG1b	219	75	Exp1		888
EG1c	80	32	Exp2		1080(960)
EG1d	55'200	110'400	Exp3		576
			Exp4		400

* Global branches only

⁺ Without max. GM

→ **PEGASOS ≈ 300'000 global branches**
→ **PRP ≈ 3 Mio global branches**

New Findings & Challenges
GMPE selection & applicability to target region

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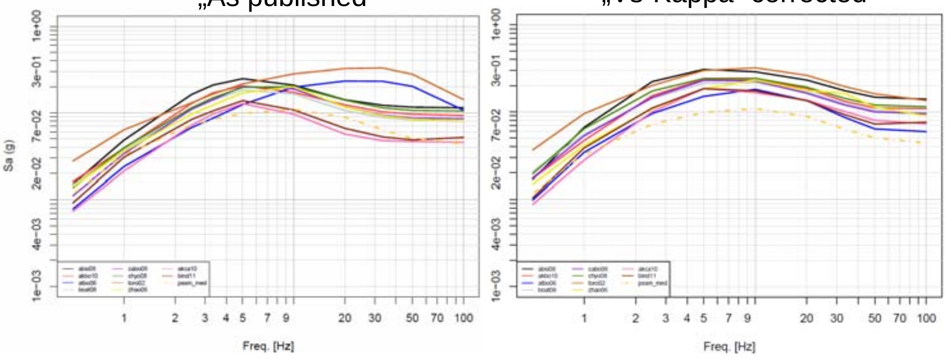
„As published“ „Vs-Kappa“ corrected



Distance (R_{JB}) = 20 km, Magnitude (M_W) = 6, Rock

Illustration of “Kappa” and Interface between SP2 and SP3

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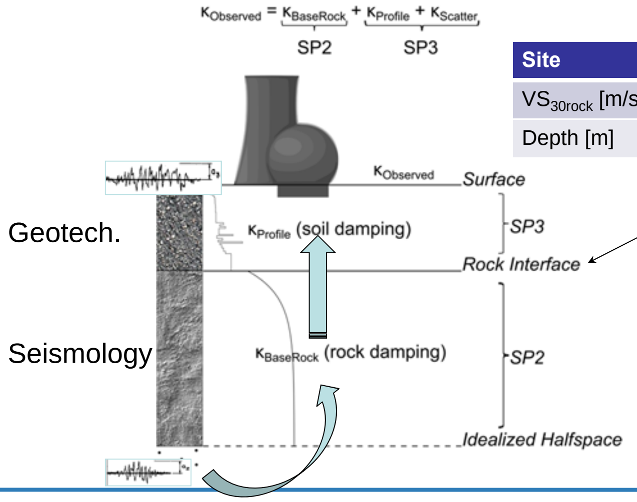

Site	KKM	KKB	KKL	KKG
VS_{30rock} [m/s]	1100	1800	2200	2500
Depth [m]	-38	-80	-100	-28

New Findings and Challenges Vertical Ground Motion

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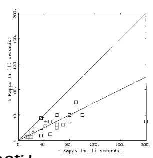
- **For the evaluation of the vertical ground motion available V/H models have been selected to be applied to the horizontal rock hazard.**
- **SP2 consistency issue: The horizontal GMPEs have been adjusted to be applicable to Switzerland (by „Vs-kappa“).**
  - The available selected V/H models have not!
  - Applying actual empirical V/H models to corrected horizontal hazard is not consistent
  - No empirical V/H models for real hard rock conditions (>1500m/s) are available → Problem: what is the vertical kappa and how to correct?



- **SP3 consistency issue: The horizontal soil hazard evaluation takes non-linearities into account.**
  - Most of the selected V/H models for soil don't!
  - Applying native V/H models for soil is not considering decrease in GM and possible truncation.

Leassons Learned
Technical and Scientific Aspects (cont.)

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- **Selection and weighting of GMPEs in the light of their applicability to the Swiss specific conditions and all the necessary corrections was/is not straightforward!**
  - The GMPEs and their weights are still the biggest contributor to the uncertainties in the SP2 models.
- **The «host-to-target» (Vs-Kappa) corrections used in PRP are defining a new state-of-the-art. The newly developed correction method represents a major improvement, but it is taking time to fully understand how these new methods are best applied and have been tested in the broader ground motion community.**
  - In other studies, such corrections have usually not been applied, or were not necessary as appropriate regional models could be used.

Sensitivity Histograms ("Tornado" Plots)
Explanatory Sketch

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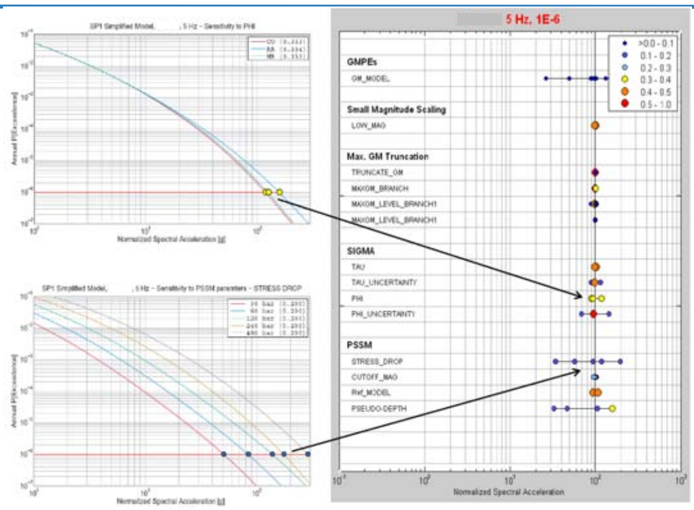

Change in Uncertainty With Respect to PEGASOS for the Rock Hazard

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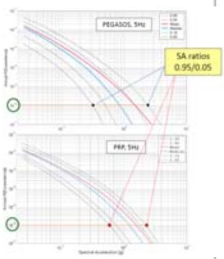

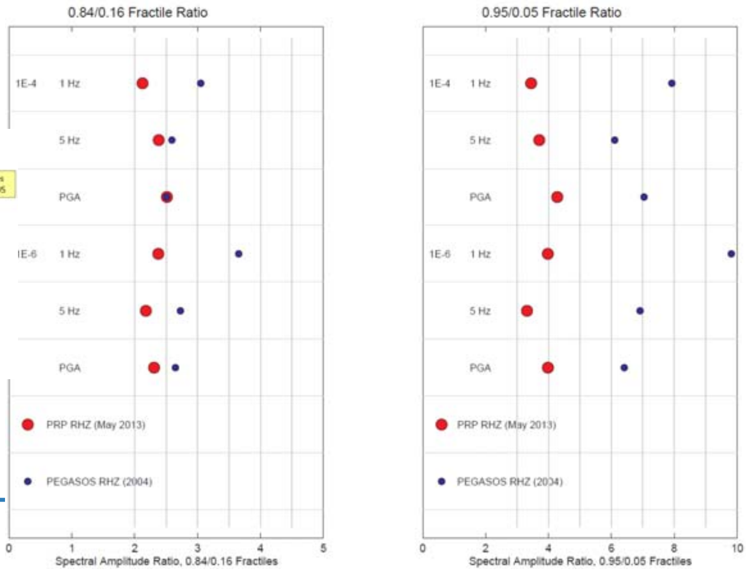

Conclusions

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Conclusions
Results and Robustness

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- **Critical facilities deserve a site specific assessment**
- **SSHAC process is not suitable for research within a commercial application project**
  - Aim of the project is a robust engineering result
- **Credibility of the results**
  - A lot of testing with various approaches was done (SOM, Intensity Testing, Mixture Model, Finite Fault Simulations, Centering,…), which helped to develop a better understanding about the models and their limitations

Conclusions
Results and Robustness (cont.)

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- **The evaluation and proper quantification of uncertainties is the real challenge**
- **The PRP has achieved a better quantification of the uncertainties**
  - Collection of more data helped to improve models
  - Clearer separation and identification of variability between SP2 and SP3 (to avoid double counting)
- **Parameters and constraints for host-to-target conversion ("Vs-Kappa" correction) are difficult to define, but a key contributor**
  - Improvement of science necessary and model developers need to put more emphasis on hard rock conditions and small magnitude data

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Thank you very much for your attention!

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