EP3: Entwicklung eines Verfahrens zur hochauflösenden, manuellen und automatischen Ortung und Charakterisierung induzierter, seismischer Ereignisse in Tiefengeothermieprojekten

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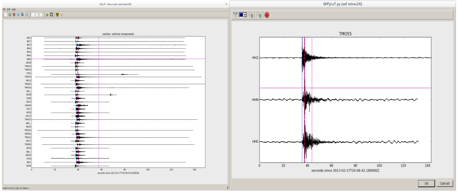
PyLoT - Python Picking and Location Tool (RUB/BESTEC)



- Consistent determination of phase-onset times (manually and automatically)
- Iterative automatic picking
- Probabilistic uncertainty determination of timing errors of derived onsets
- Comparison of automatically and manually derived onset times based on probabilistic density functions
- Locating of EQ's using NonLinLoc

PyLoT - Python Picking and Location Tool (RUB/BESTEC)

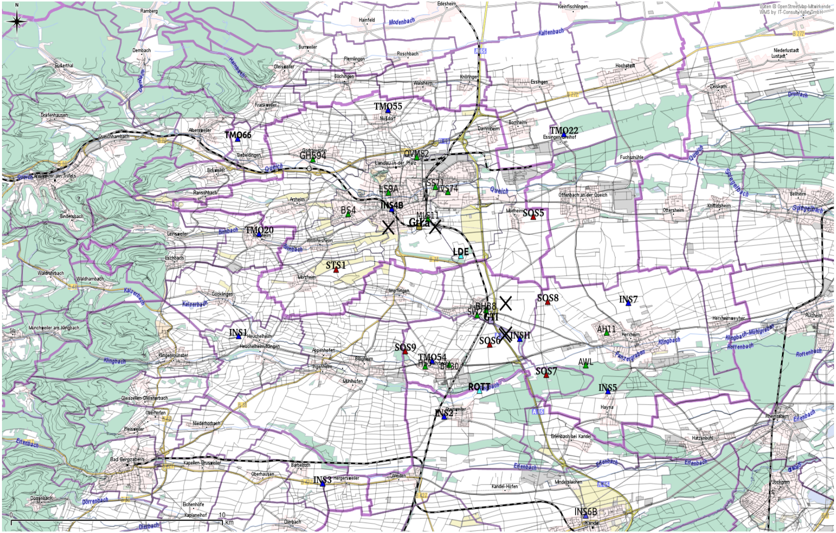
PyLoT is available from:
github.com/seismology-RUB/PyLoT

Insheim Power Plant

- Startup: October 2012
- Geothermal water temperature: $> 160^o C$
- Flow rate: $40 - 85 l/s$
- Power:
  - electrical: $\approx 4.8\ MW$
  - thermal: $\approx 6\ MW$
- 3 wells: 1 production & 2 injection wells

Seismic Monitoring

Seismic Network, Emission- and Immission-Network



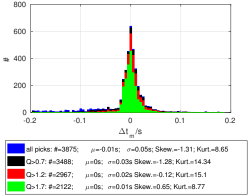
△ permanent stations of operator, △ temporary stations of BGR, △temporary stations of DMT,

△ permanent stations of LGB RLP

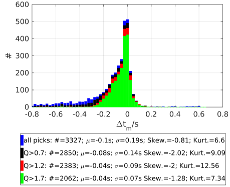
Guralp acquisition system:

- CMG6T 1Hz-seismometer
- CMG-D24 data logger
- CMG-EAM (embedded acquisition module)
- near-real time processing via GSM modem, CMG-NAM (network appliance module), and InSite software (ASC)
- 100-Hz data transmitted to data center (Landau), continuous recording of 400-Hz data

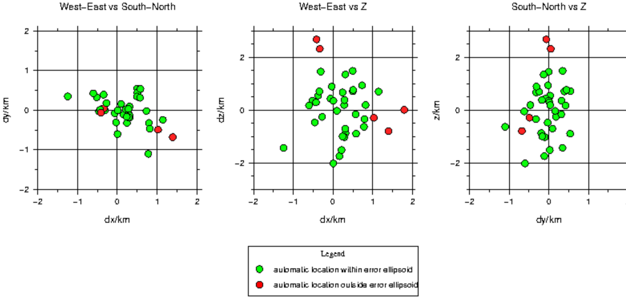
P-picks: $0s \pm 0.01s$



S-picks: $0.04s \pm 0.07s$



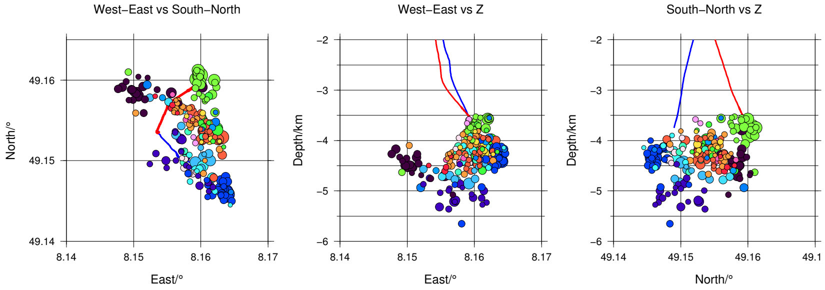
- Comparison with NLLoc-relocations obtained with automatic and manual picks.
- 40 events with ≥ 10 P and S picks
- hor. error $\pm 0.45km$, vert. error $\pm 0.95km$



Similarity Detector (CAU)

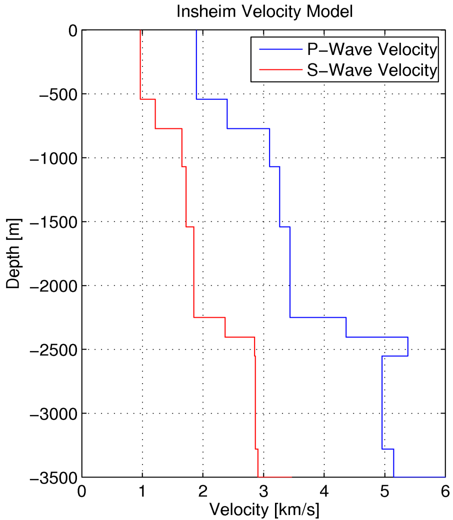
HypoDD-Location of clusters in Insheim reservoir

- Using 20 master events 2012-2015
- 374 detektions (80% of MAGS detektor, 76% of STA/LTA)
- 99 new events against STA/LTA, 45 new events against MAGS
- $\approx$ 1% miss detections (4)



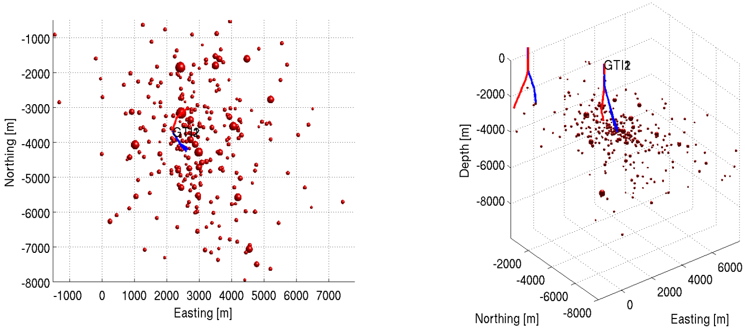
Locating Microseismicity: Initial Velocity Model

10-layer 1-D Velocity Model



Locating Microseismicity: Routine locations of seismic events

HYPOSAT, correction for elevation (P: 1.45 km/s, S: 0.49 km/s), no station corrections, velocity model derived from VSP measurements, RMS=0.12 s



Insufficient location accuracy due to complex velocity heterogeneities

⇒ Advanced data processing!

VELEST (Kissling et al., 1994 [a])

A program to derive a "minimum-1D velocity model"

[a] Initial reference models in local earthquake tomography, *J. Geophys. Res., 99*, pp 19635-19646.

Best approximation of a 1D-velocity model to the 3D-subsurface structures

- FORTRAN77-routine to derive 1D-velocity models and initial reference-velocity models for seismic tomography
- Solves iteratively the coupled, non-linear problem hypocenter determination - velocity model
- Iteration:
  - Solving the "forward problem" (determination of arrival times for direct, refracted, and reflected waves using a ray-tracer)
  - Solving the inverse problem (determination of a velocity model by full inversion of the least-squares (Jacobi) matrix
- Solving iteratively the non-linear problem

Good and reasonable starting model needed!

Starting Model for Inversion

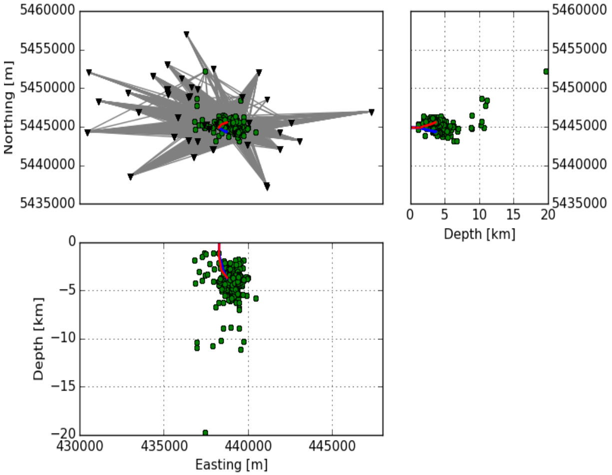
Additional a priori information from:

- 2D-seismic profiles
- VSP measurements
- Borehole stratigraphy
- Near-surface S wave velocities from microzonation (EP4)

⇒ 9 starting models for VELEST iterations:

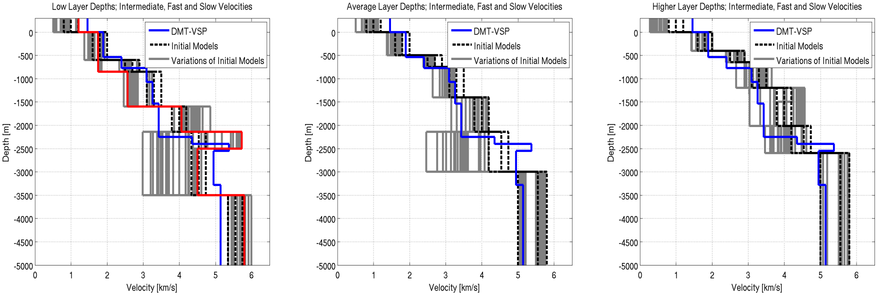
low layer depths	intermediate layer depths	high layer depths
slow velocities	slow velocities	slow velocities
intermediate velocities	intermediate velocities	intermediate velocities
fast velocities	fast velocities	fast velocities

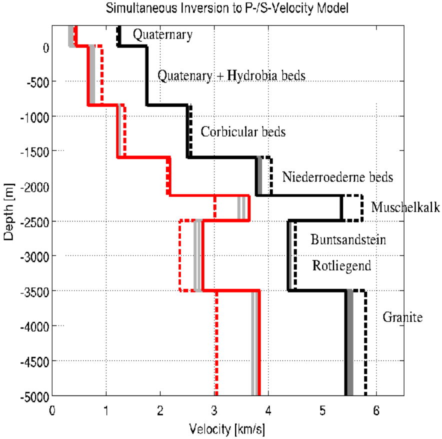
Systematic Variation of Velocity Models
Ray coverage



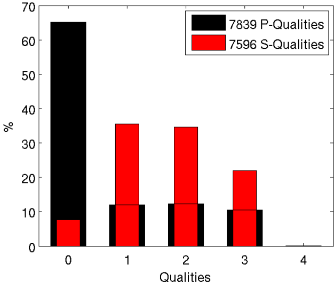
Systematic Variation of Velocity Models

Inversion to P-velocity models only



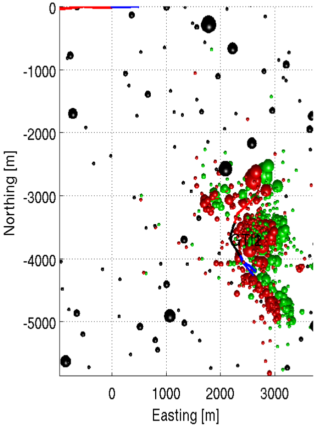


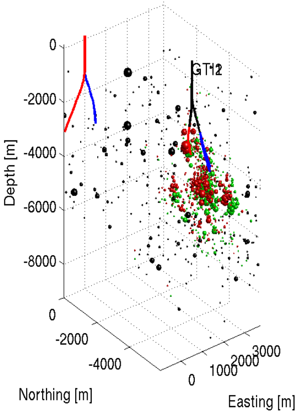
Decrease of RMS traveltime residual from 0.12 s to 0.04 s!



Weight	Uncertainty	Classification
0	$0s < \epsilon \leq 0.04s$	excellent
1	$0.04s < \epsilon \leq 0.08s$	very good
2	$0.16s < \epsilon \leq 0.32s$	good
3	$0.32s < \epsilon \leq 0.64s$	intermediate
4	$\epsilon > 0.64s$	bad (not used)

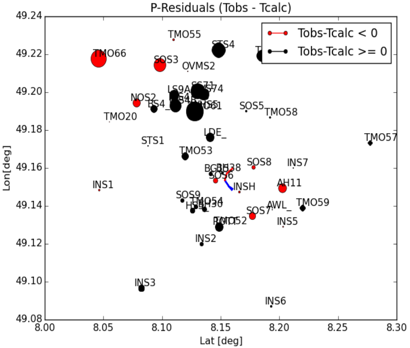
Systematic Variation of Velocity Models
Stability test



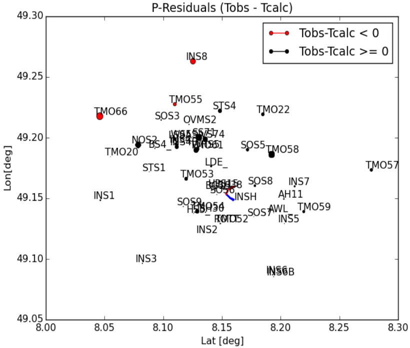


Systematic Variation of Velocity Models

Station Residuals P-Onsets

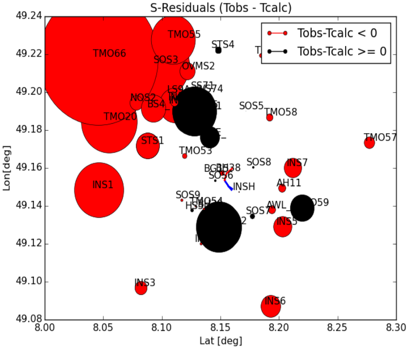


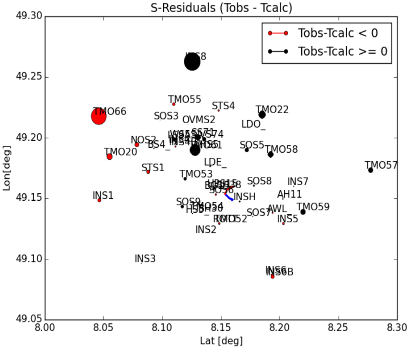
"Old" velocity model



New minimum-1D velocity model

Systematic Variation of Velocity Models
Station Residuals S-Onsets





"Old" velocity model

New minimum-1D velocity model

NonLinLoc (Lomax, A., Virieux, J., Volant, P., & Berge, C., 2000. [a])

A program to compute probabalistic earthquake locations

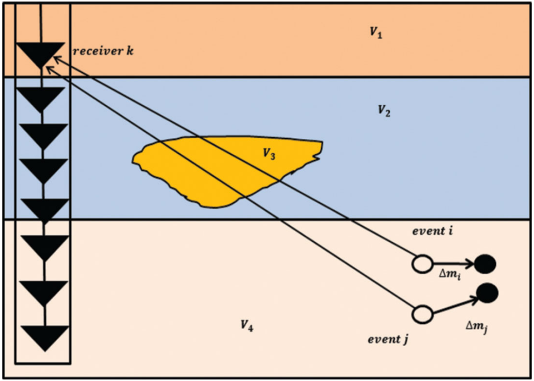
[a] Probabilistic earthquake location in 3D and layered models: Introduction of a Metropolis-Gibbs method and comparison with linear locations, in Advances in Seismic Event Location Thurber, C.H., and N. Rabinowitz (eds.), Kluwer, Amsterdam, 101-134.

- Probabilistic formulation of inverse problem
- Direct, analytical calculation of maximum-likelihood source time (reduction of 4D problem x, y, z, t to 3D problem x, y, z)
- Determination of a maximum-likelihood hypocenter, i.e. global minimum of misfit function of location likelihood function using meshgrid algorithms

hypoDD (Waldhauser, F., & Ellsworth, W.L., 2000. [a])

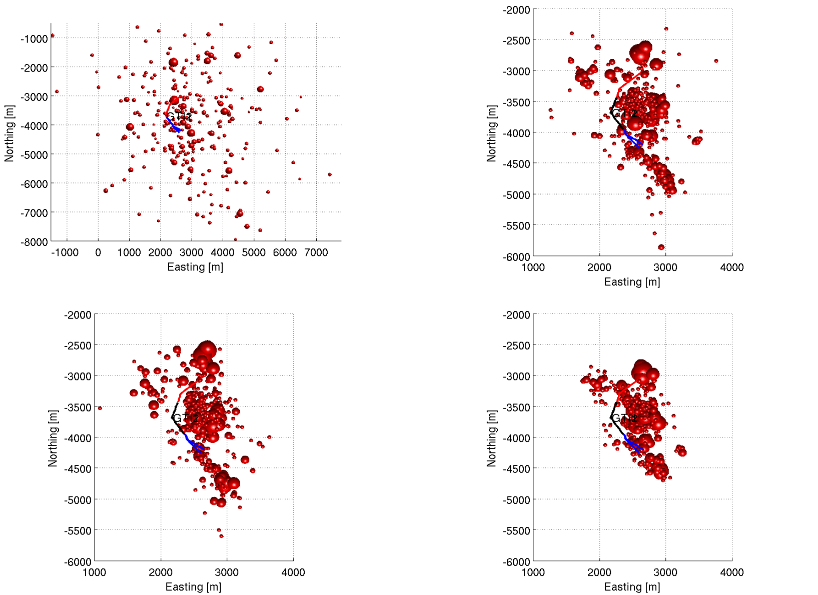
A program to compute double-difference hypocenter locations

[a] A double-difference earthquake location algorithm: Method and application to the northern Hayward fault, California, *Bull. Seism. Soc. Am.* **90**, pp 1353-1368.

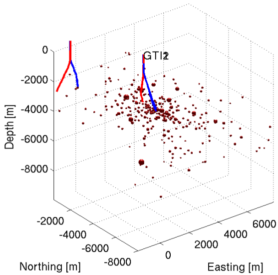


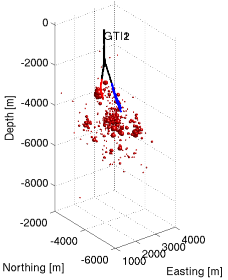
- Hypocentral seperation between two earthquakes is small compared to the event-station distance and to scale length of velocity heterogenities
- ⇒ Assumption of homogenious velocities within source region

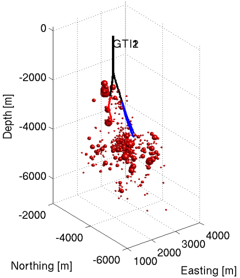
Highly accurate locations: HYPOSAT ⇒ VELEST ⇒ NLLoc ⇒ hypoDD

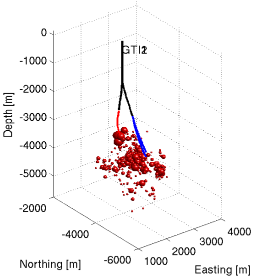


Highly accurate locations: HYPOSAT ⇒ VELEST ⇒ NLLoc ⇒ hypoDD





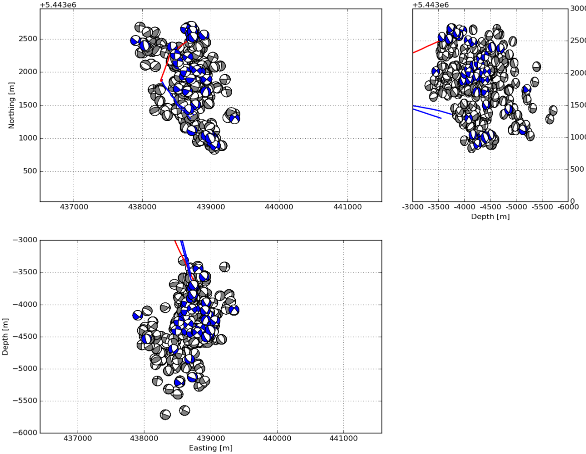




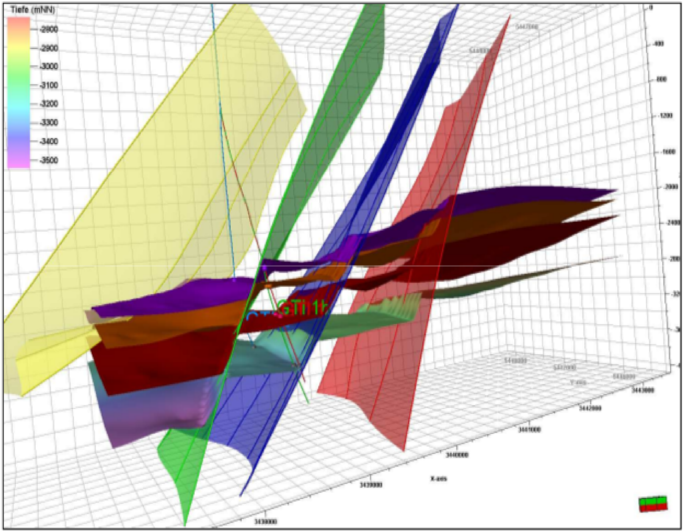
Fault Plane Solutions

Source mechanisms derived with HASH [a])

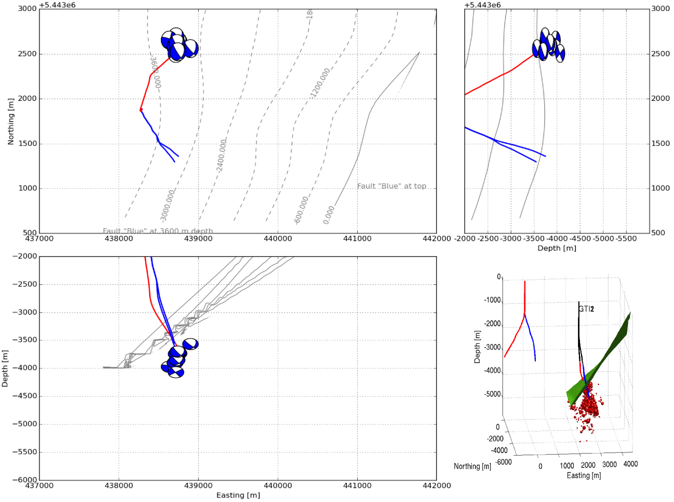
[a] Hardebeck, J. & Shearer, P.M., 2002: A new method for determining first-motion focal mechanisms, Bull. Seism. Soc. Am., 92, 2264-2276



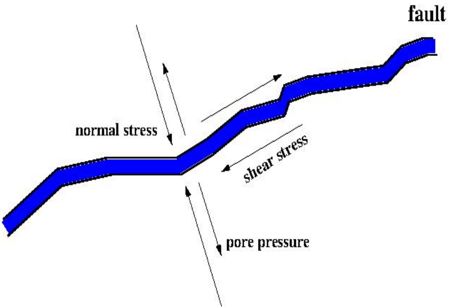
Fault Plane Solutions
Correlation with Faults



Fault Plane Solutions
Correlation with Fault



Seismicity at Production Well
Principle of Fluid-Injection Induced Seismicity



Thank you very much for your attention!