The DRG seismic experiment in Krafla

New seismic methods for mapping magma intrusions/pockets where geothermal heat mining is taking place

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Aim:

Study propagation of seismic waves in the Krafla volcano and look for signals from known magma, where heat mining is taking place:

The original proposal:

1. Scrutinize data from the permanent seismic network in Krafla
2. Deploy 20 additional seismic stations and record for
   4 months
3. Undershooting by distant earthquakes and explosives
4. Detailed analyses of all data (seismic, EM and bore-hole data) to characterize the deep roots of the the Krafla geothermal system.

Data collection was to be managed by ISOR and UU

Most of the data processing and interpretation was to be done by a PhD student at UU and ISOR expert(s)

Actual setup and data acquisition

- It was decided to put seismometers on dense profiles in the hope of recording un-aliased reflections
- At first, 20 stations on a dense profile between the test wells during the IMAGE VSP experiment, late May to early June 2014
- From June 25th to 31st the 20 stations were installed at 200-300 m intervals on two profiles,
  14 stations on a 2.5 km SSW-NNE profile and
  7 stations on a 1.3 km NW-SE profile
- August 5th to 7th and Sept. 1st to 2nd all the stations were serviced
- The Network was pulled out Oct. 6th and 7th
- 90% data recovery
- The recorded data were loaded into the SeisComp seismic software and data base at ÍSOR

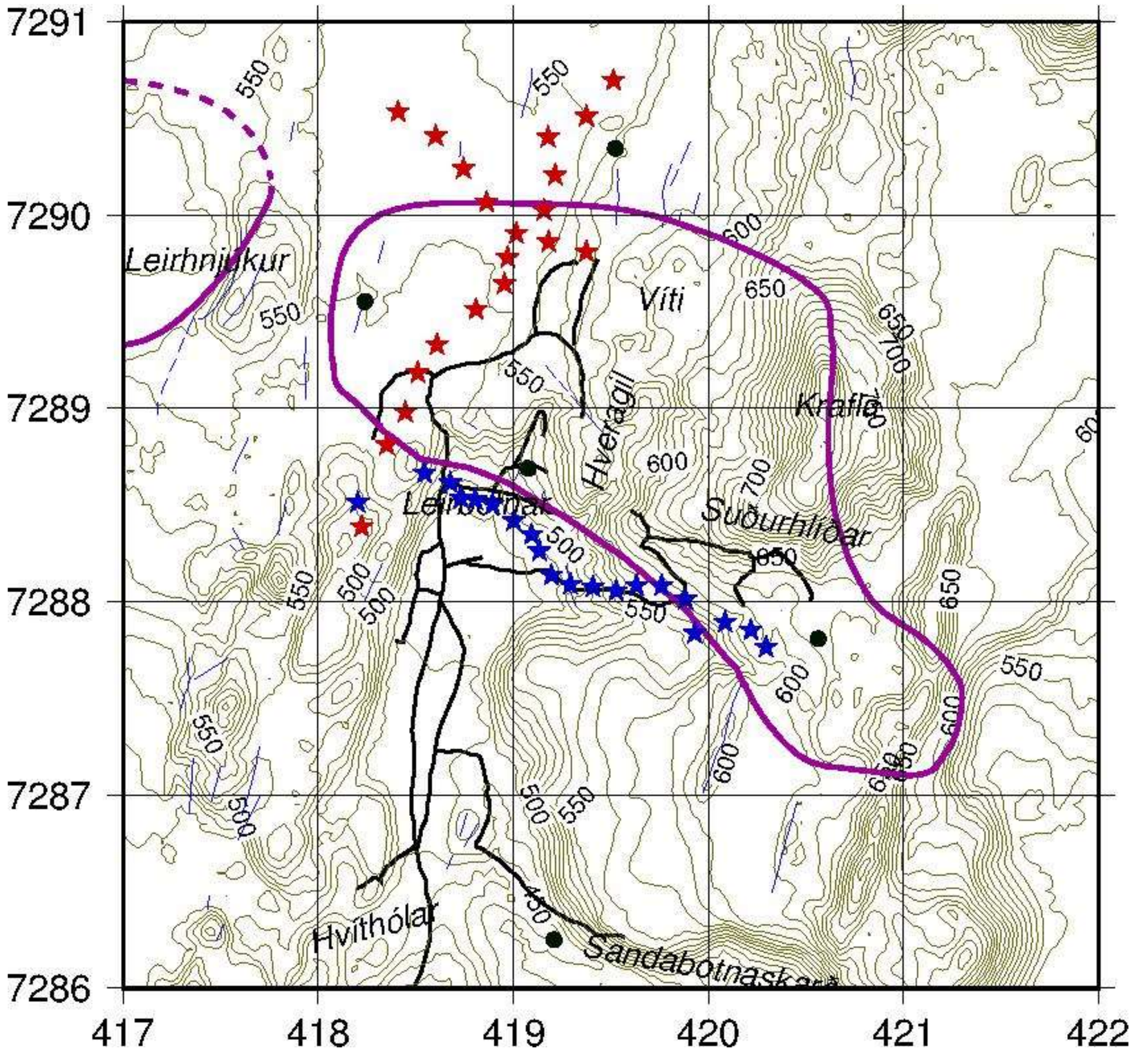
The DRG seismic network

Blue stars are seismic stations during VSP

Red stars during DRG recording

Black dots are Permanent stations

Purple lines show boundaries of S-wave shadows

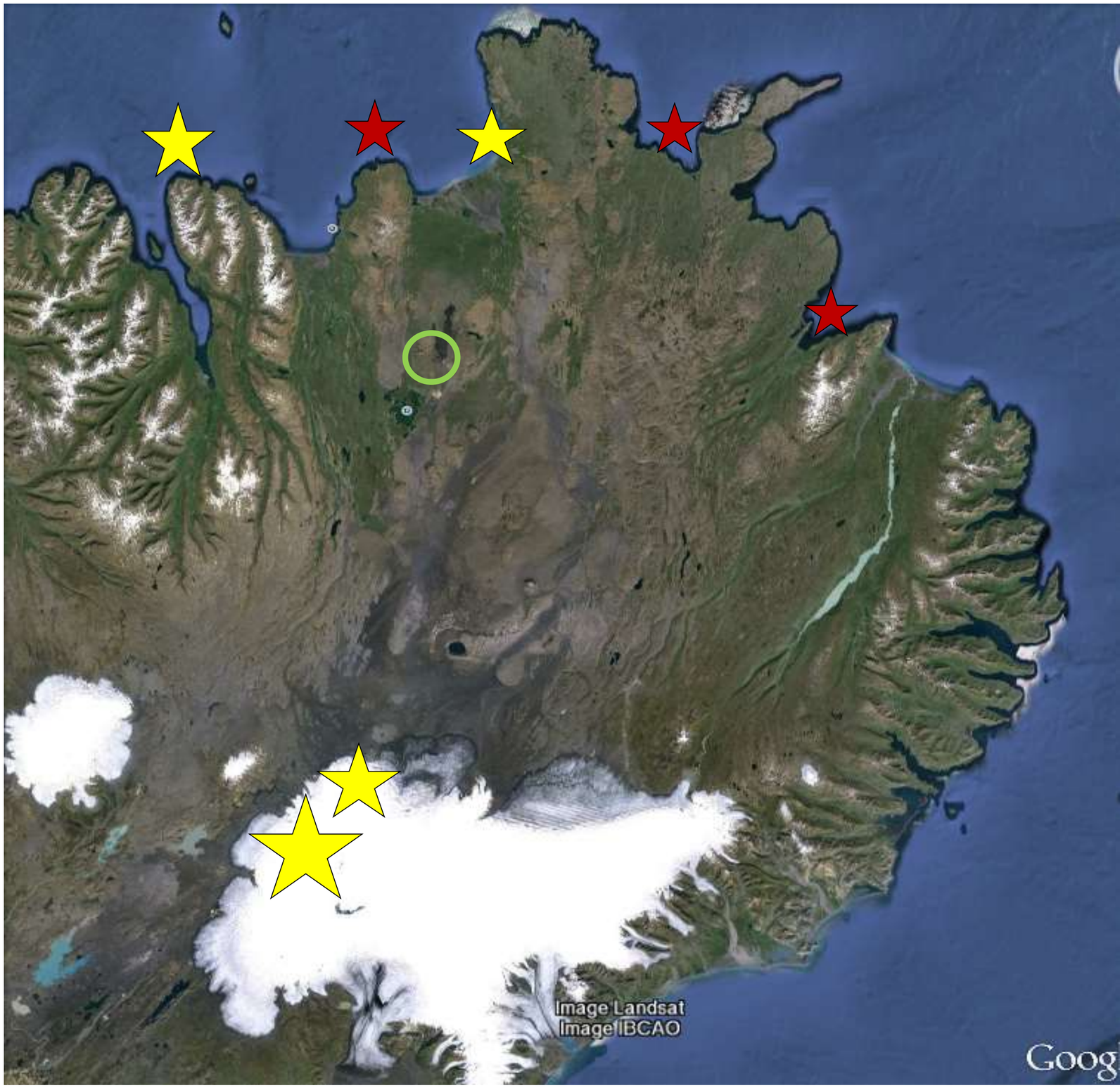


Undershooting and distant quakes

Krafla area
(green circle)

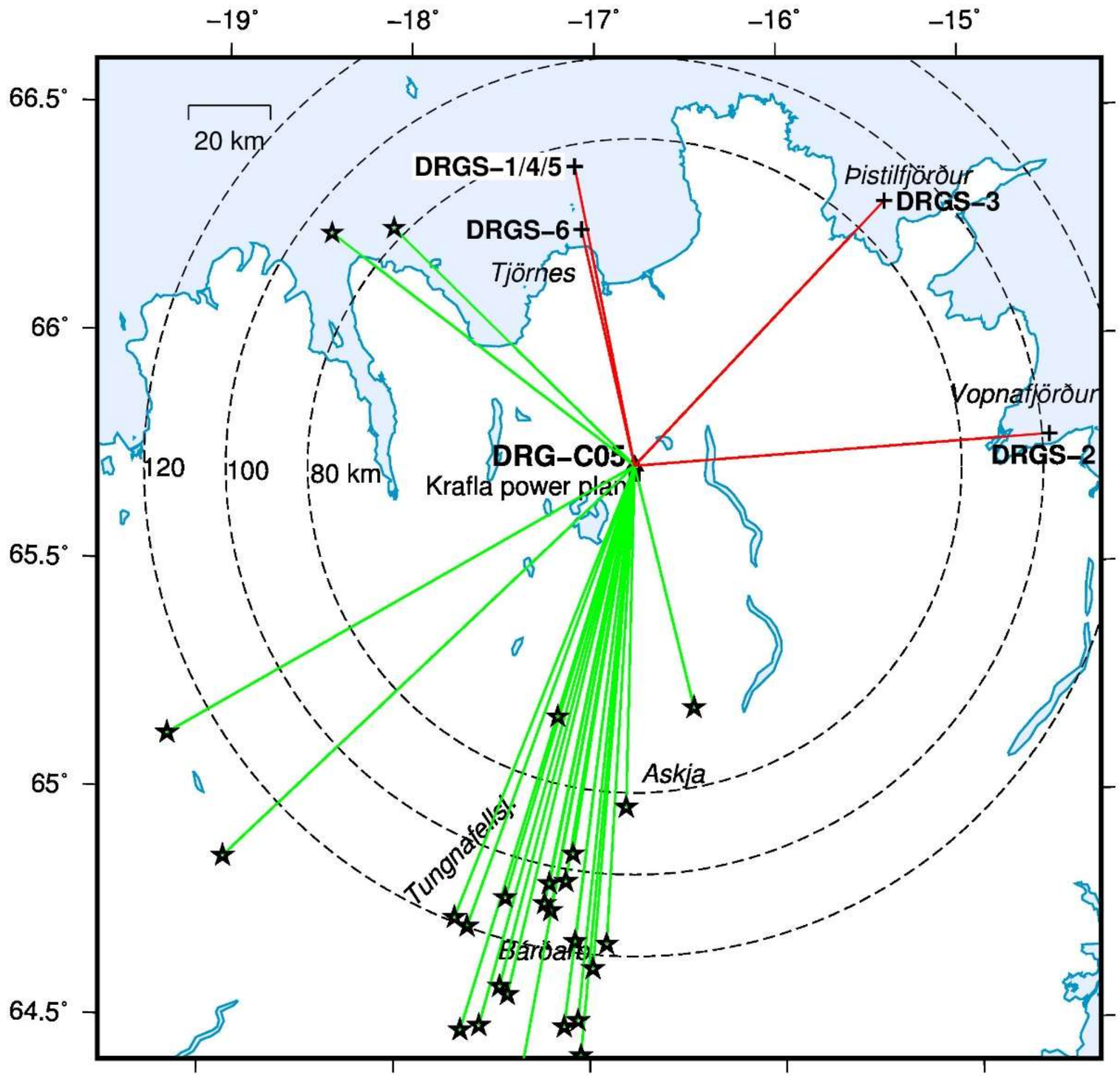
Distant earth Quakes
(yellow stars)

Explosives (4 to 9 September 2014)
100-300 kg TNT
(red stars)

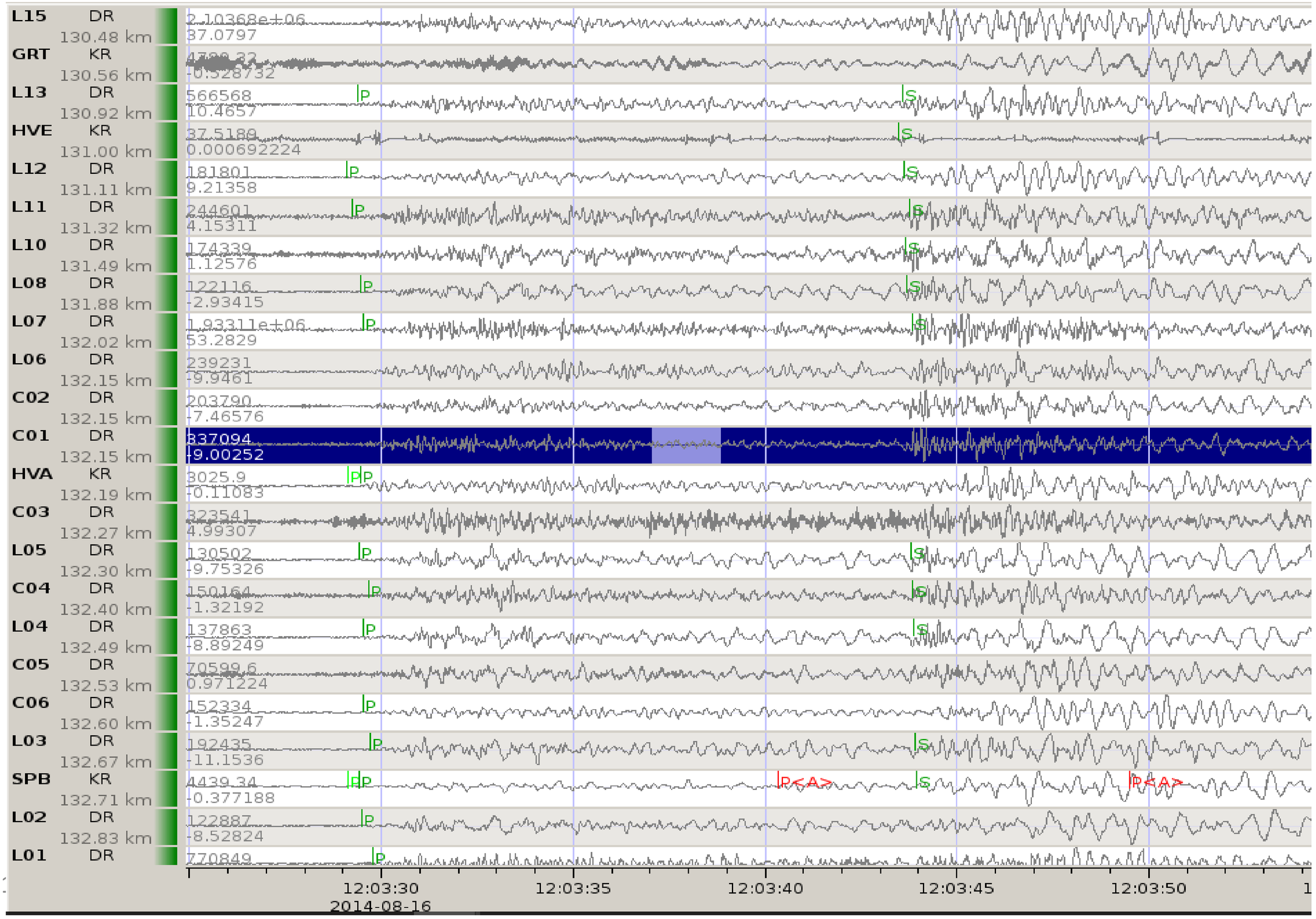


Picked shots and distant earthquakes

100 to150 distant earthquakes have been picked and 4 shots (the figure shows examples)

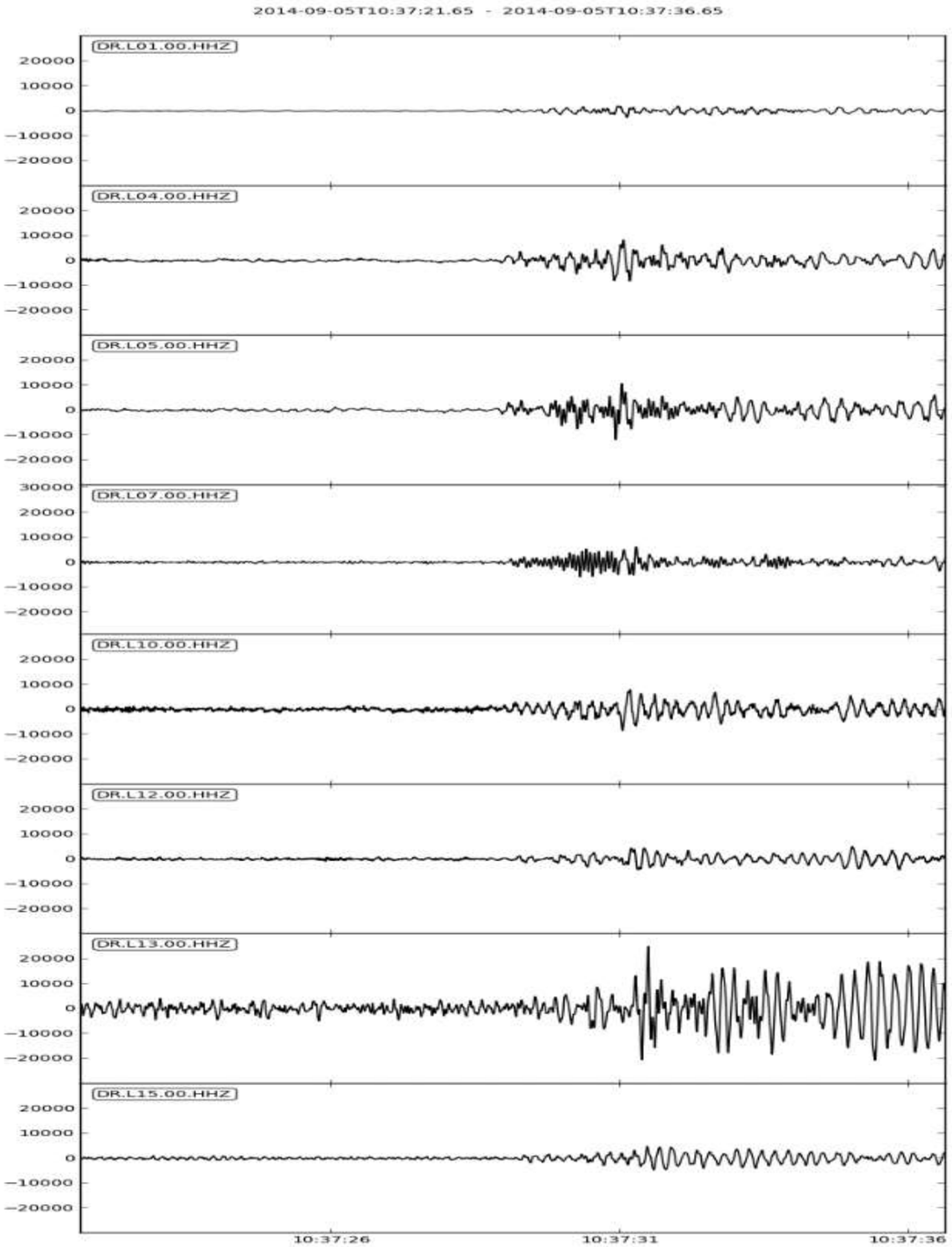


Distant earthquake in Bárðarbunga

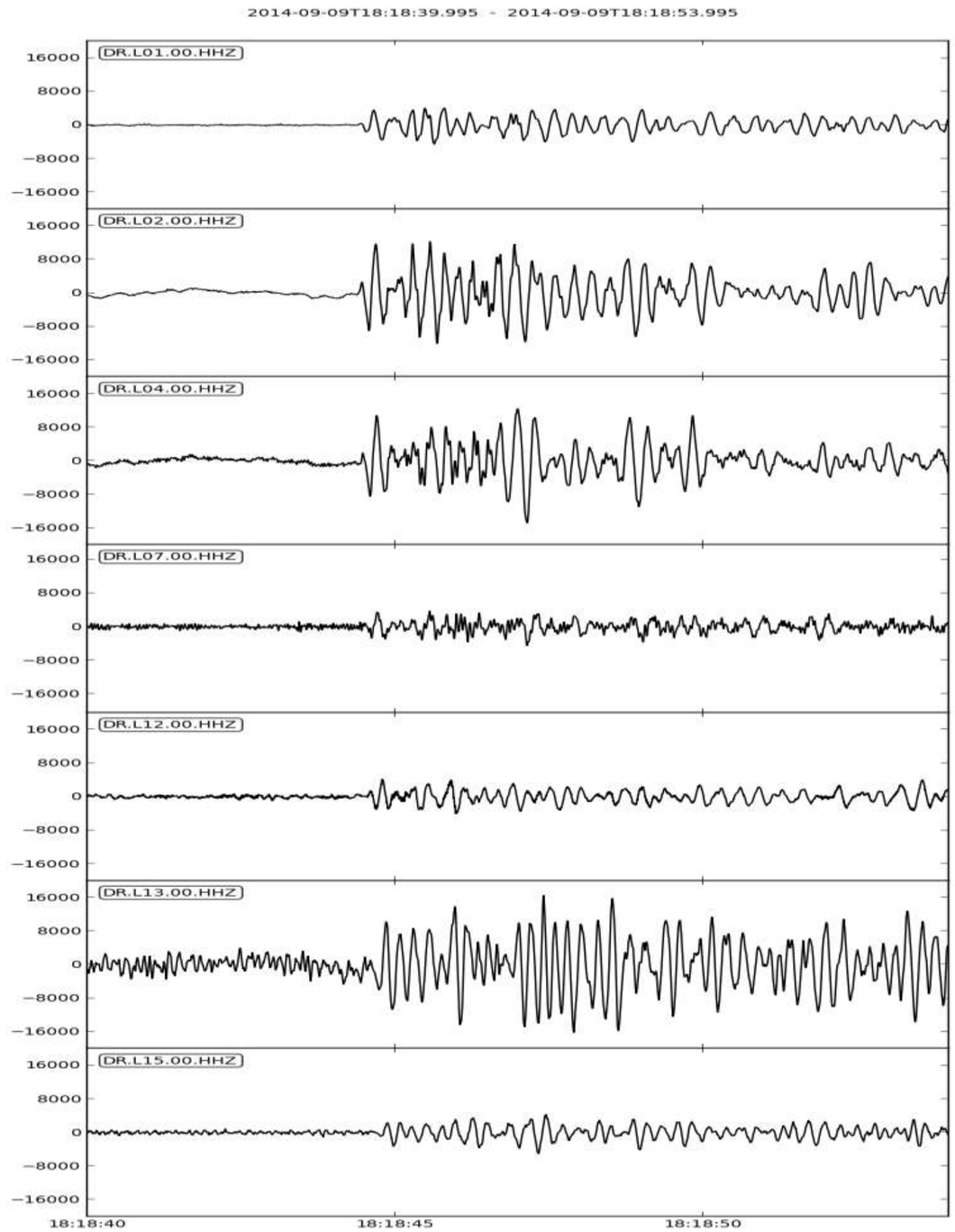


Distant shots

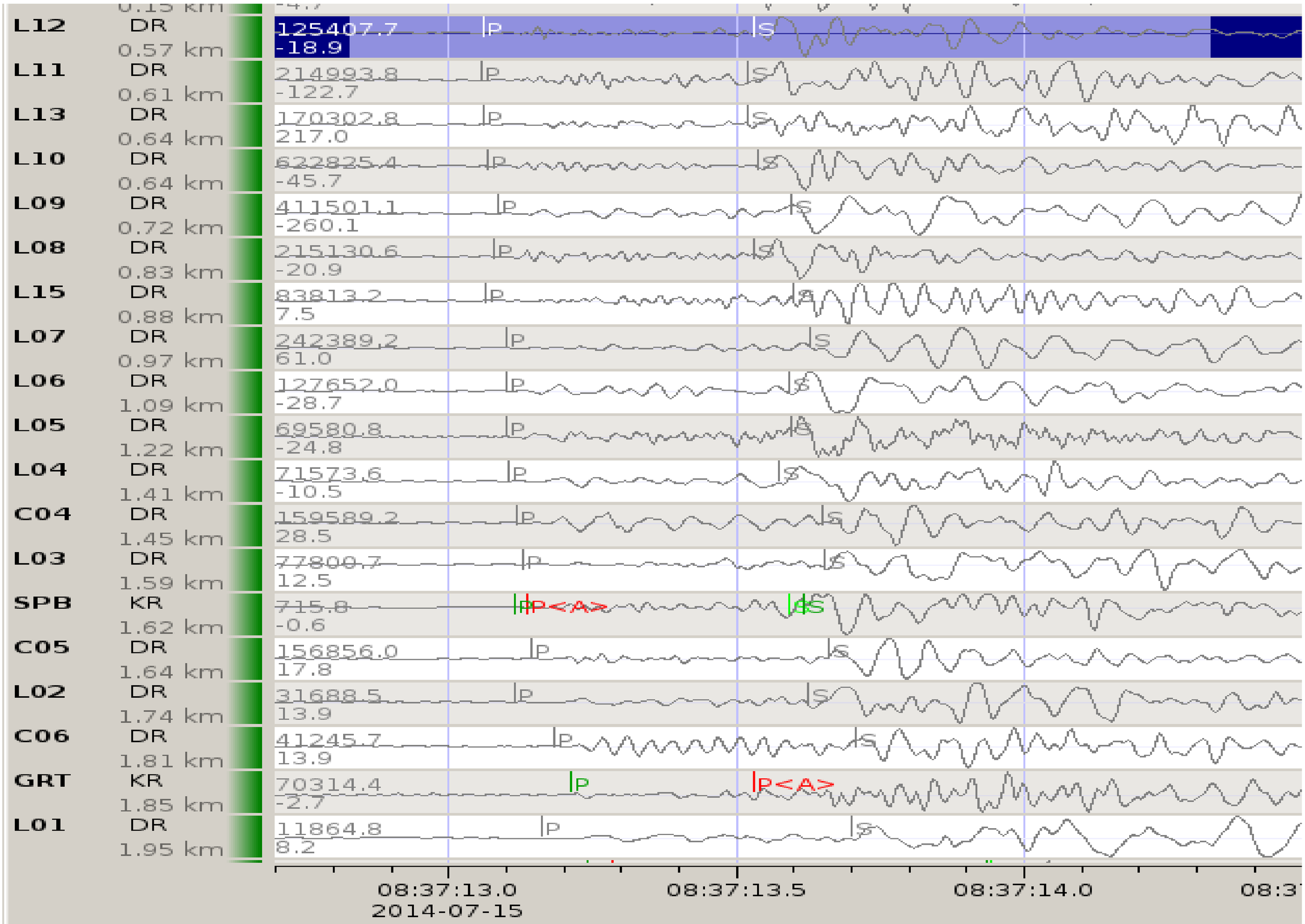
Vopnafjörður



Mánáreyjar



Local earthquake in Krafla



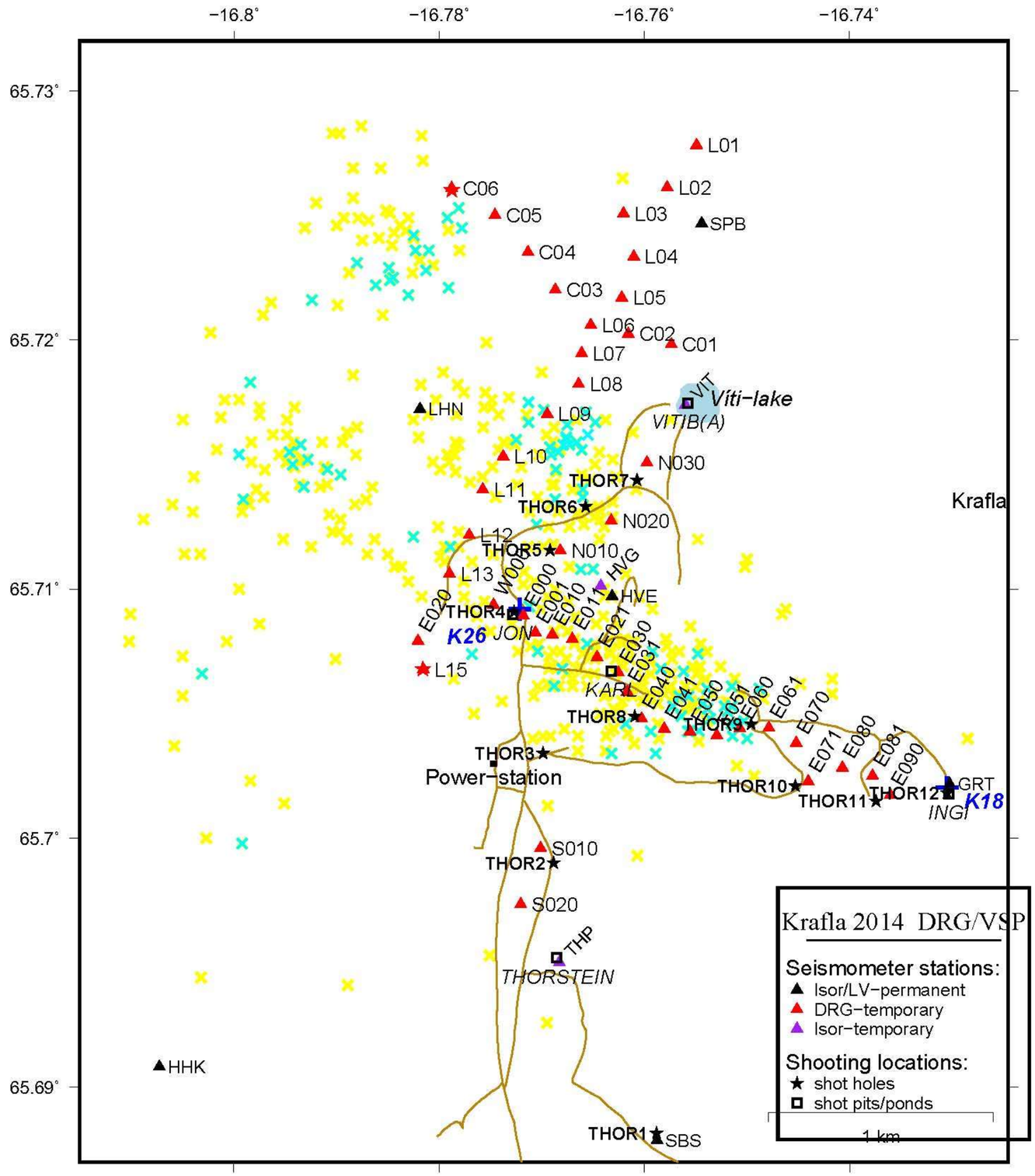
Picked local earthquakes during DRG installed

Yellow

picked and located by the permanent Network

Light blue

picked on the DRG network



Data processing and interpretation

UU did not have PhD student available for the data processing and interpretation as planned. This caused a delay of the project.

The coordinator got in contact with a seismic group at Cornel University in USA, led by prof. Larry Brown. The group at Cornell had been working on ideas similar the ones behind the DRG seismic experiment and the data turned out to be very valuable to test their ideas.

A PhD student at Cornell, Doyeon Kim, got the DRG seismic data for processing and interpretation.

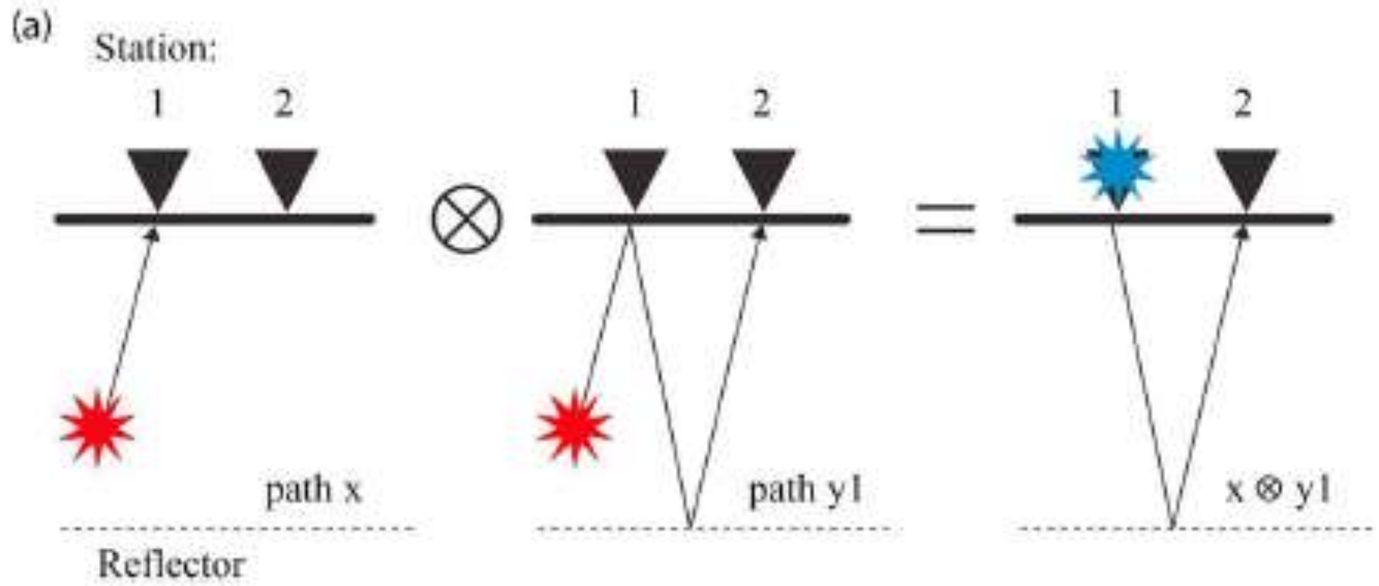
The Cornell group applied two new and innovative processing methods:

Virtual Reflection Seismic Profiling (VRSP) and

Reverse Vertical Seismic Profiling (rVSP)

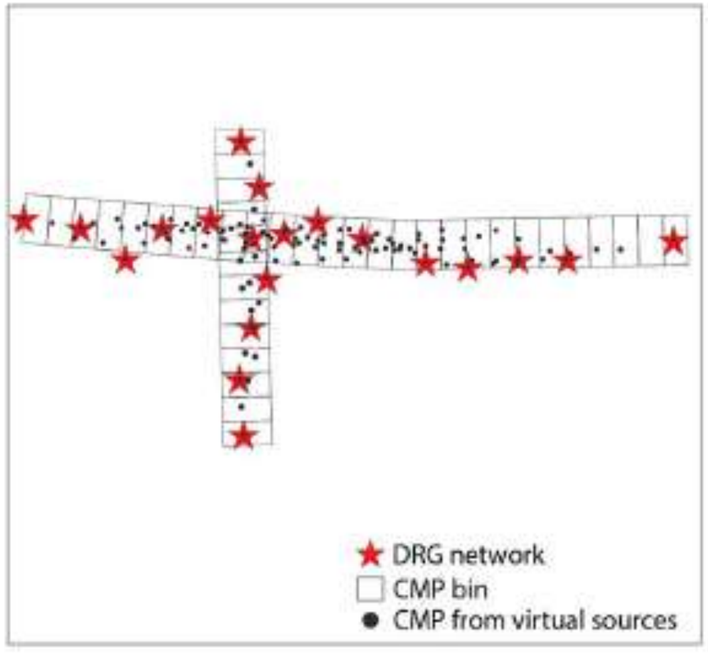
Virtual Reflection Seismic Profiling

Convolving the earthquake coda at station 1 with the seismogram at 2 can pick up the wave that is reflected down from 1 and back to 2. Each seismic station can hence become a virtual source.

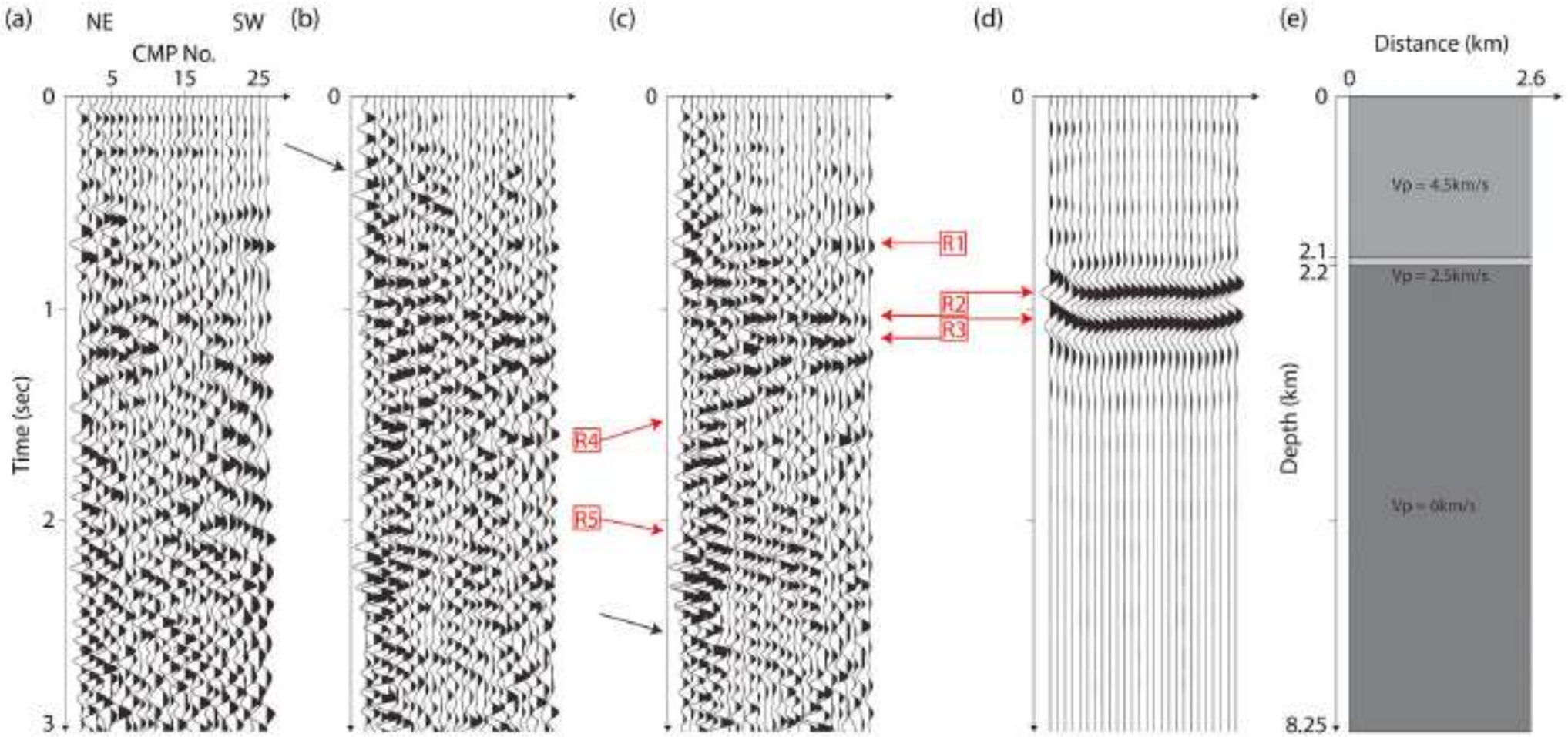


(*From Kim et al. 2017)*

Seismic traces from the virtual sources can be processed by standard reflection seismic methods; collected into CMP gathers, NMO corrected and stacked.



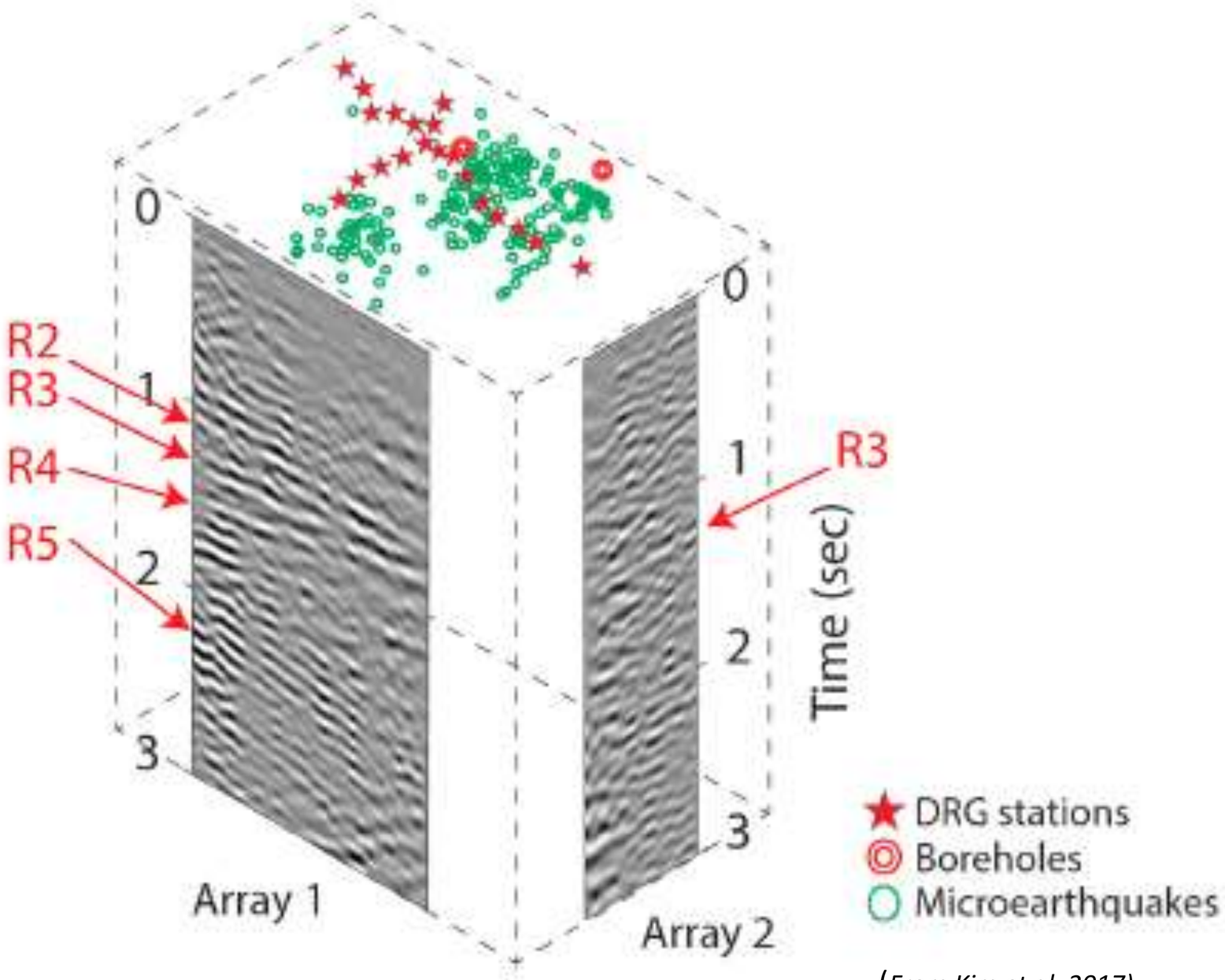
Stacked section along the NE-SW DRG profile and synthetic model



(*From Kim et al. 2017)*

Stacked sections for the two DRG profiles

Reflector R2 corresponds magma hit in IDDP-1



(*From Kim et al. 2017)*

Reverse Vertical Seismic Profiling (rVSP)

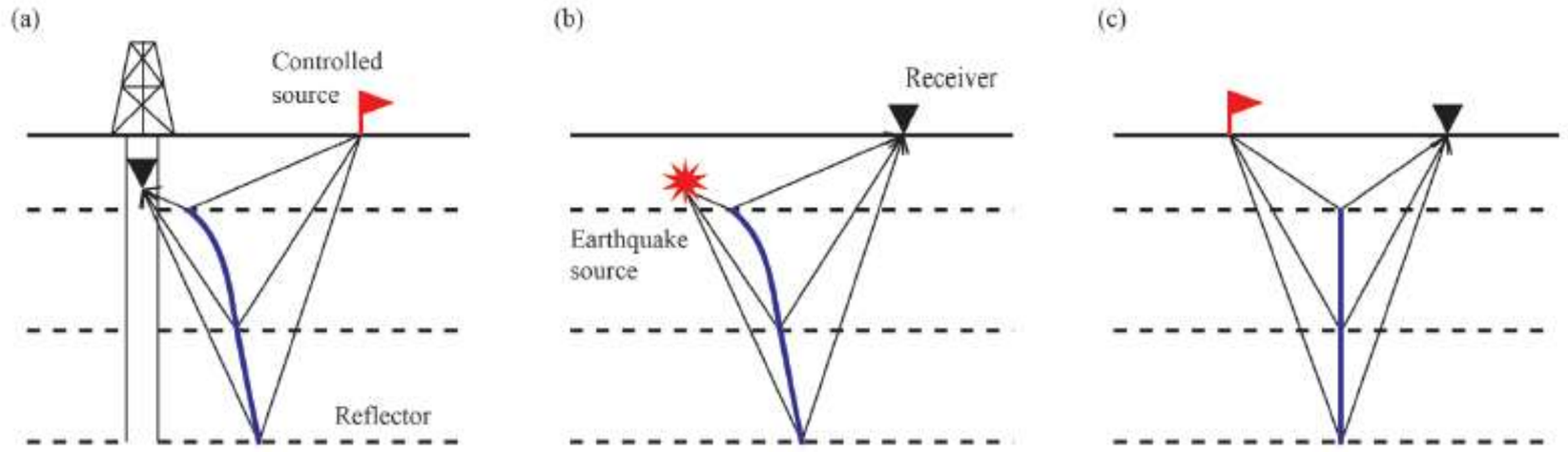


Figure 2. (a) Representative geometry for conventional VSP survey, (b) rVSP using earthquake as a source, and (c) conventional artificial surface source (CMP) seismic reflection survey.

(From Kim et al., accepted by GRL)

In VSP, the source is on surface and receiver down hole

In rVSP the source is in the subsurface and receiver on surface

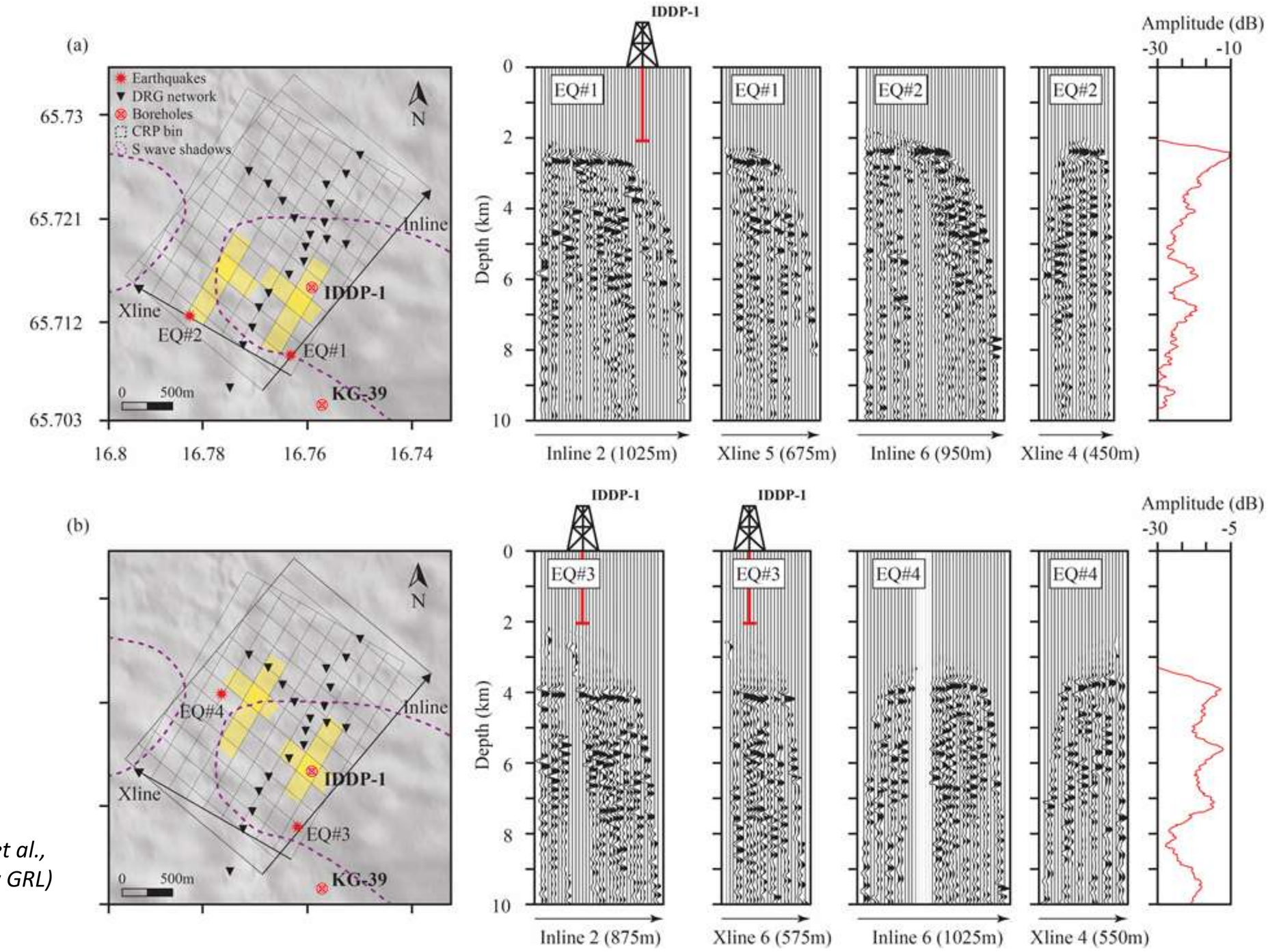
CRP not mid between source and receiver leads to more complicated collection of CRP gathers (but well established from oil industry)

Sensitive to hypocentre location accuracy

Example of rVSP processing of the DRG data

4 earthquakes

CRP binned (yellow squares) to produce reflection sections



(From Kim et al., accepted by GRL)

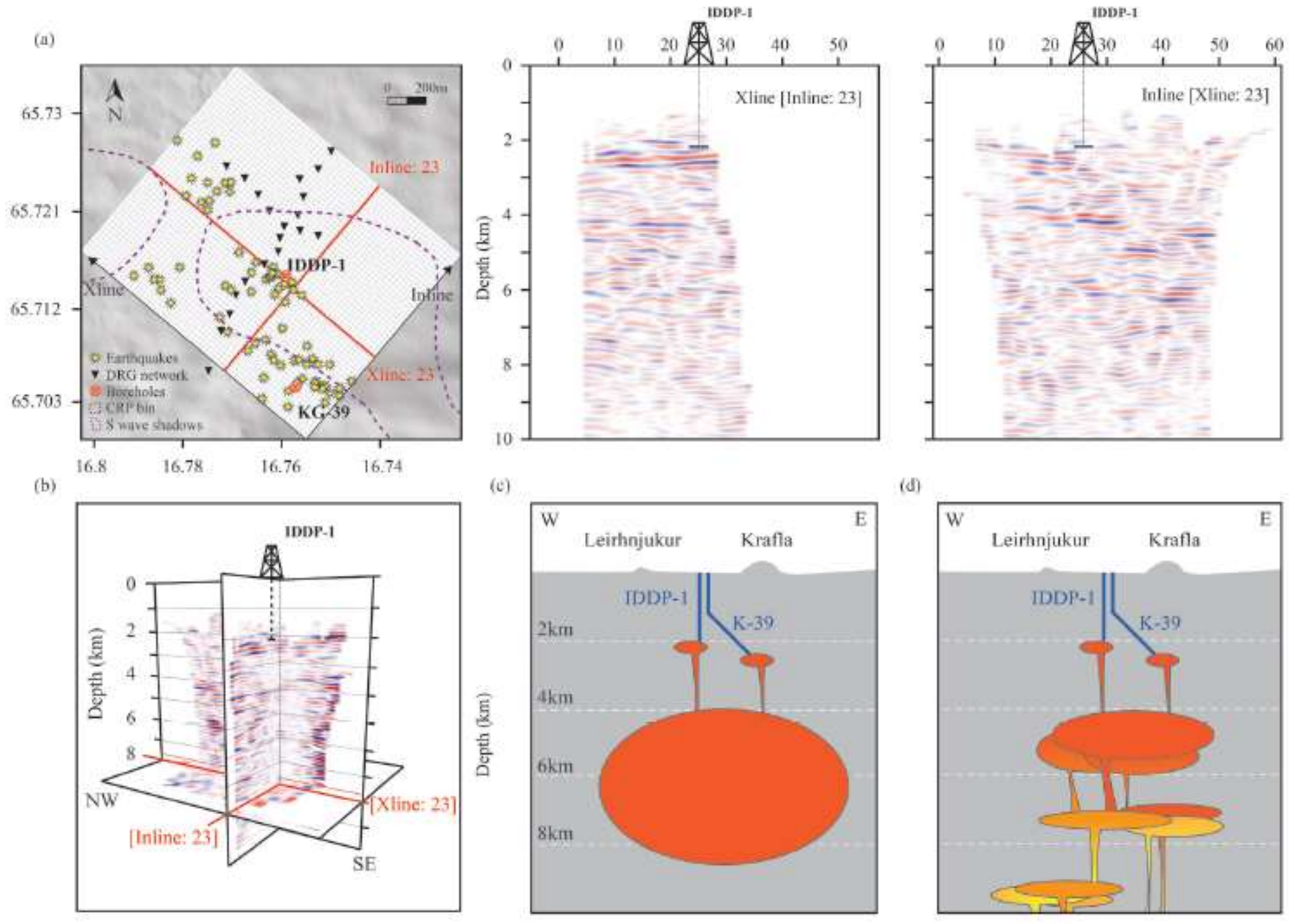
The final results of rVSP processing
Stacked over 120 earthquakes

Clear reflection seen right below IDDP-1

Reflections also seen deeper down (e.g. at 4 km depth)

No dominant reflection indicating big main magma reservoir but a sequence of reflectors

Indicating distributed magma pluming system



(From Kim et al., accepted by GRL)

Conclusions

- In the DRG seismic experiment in Krafla, a high quality data were recorded for three months on two dense profiles over an S-wave shadow in Krafla.
- The data have been loaded into the SeisComp database at ISOR (available for further studies).
- Recorded data from local earthquakes have been processed by the seismic group at Cornell University, using new innovative approaches; Virtual Reflection Seismic Profiling and reversed Vertical Seismic Profiling.
- Both processing approaches reviled reflectors, reflecting seismic waves from earthquakes. The most prominent one can be associated with the magma hit in IDDP-1, where heat mining is taking place.
- A sequence of deeper reflectors suggests a distributed magma pluming system with sills, rather than a single big magma reservoir in the Krafla volcano.

Conclusions (Cont.)

- The DRG seismic experiment in Krafla has shown that recording local seismicity by dense arrays of seismometers and applying new and advanced processing methods can be used to study reflectors in the shallow crust in some details.
- Drilling into magma just below 2 km in K-39 and IDDP-1 in Krafla came as a surprise. Its presence had not been detected by surface studies.
- The methods and results described here indicate that we might be on the right track in finding a (long sought) method to detect magma (heat sources) at shallow crustal levels.
- Encouraged by the positive results of the DRG experiment, Cornell University, in collaboration with ÍSOR, is now seeking funds for a similar large scale survey in Krafla; deploying about 600 seismic stations in a dense (50m x 50m) grid in Krafla, as a part of the “Krafla Magma Test-bead” project.