

# 15 November 2017 Pohang Earthquake

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Sungshil Kim<sup>2</sup>, Su Young Kang<sup>1</sup>, Wooseok Seo<sup>1</sup>**

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*<sup>3</sup>Seoul National University*

**6 March 2019**

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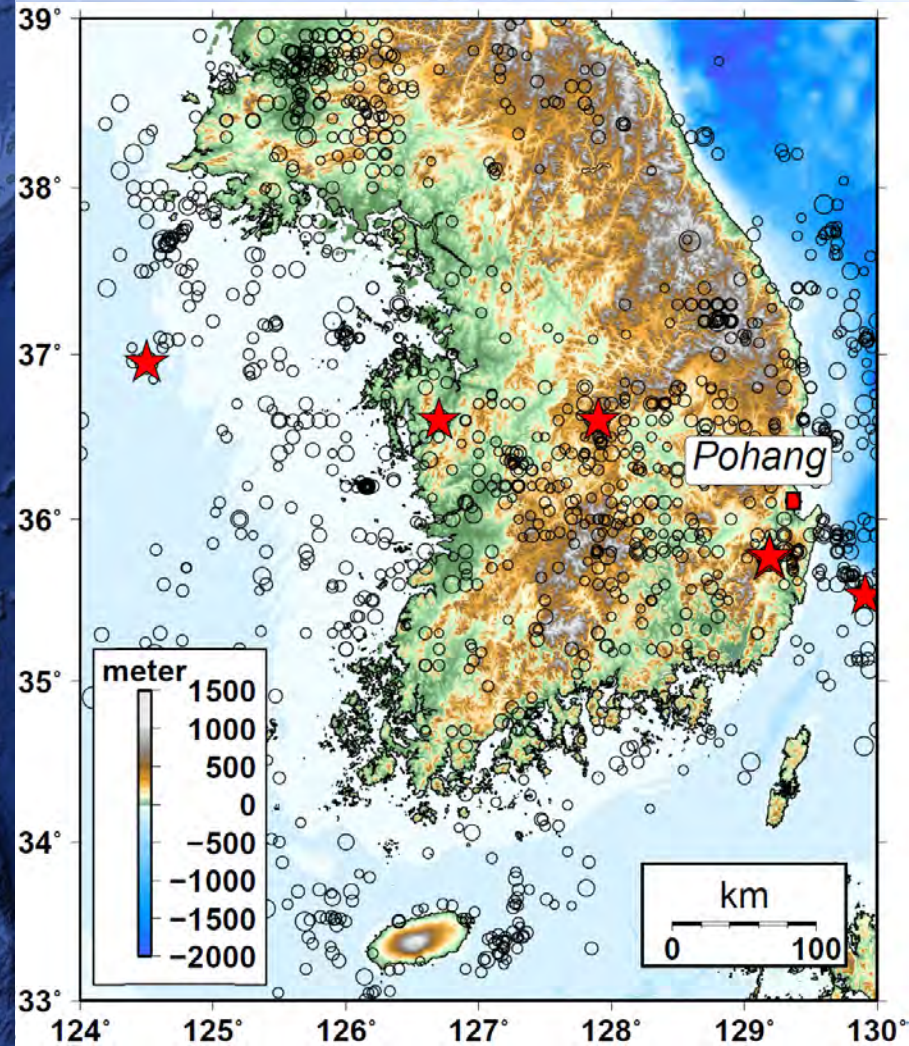
**I . Seismicity in the Pohang Region**

**II . Fluid Injections and Seismicity**

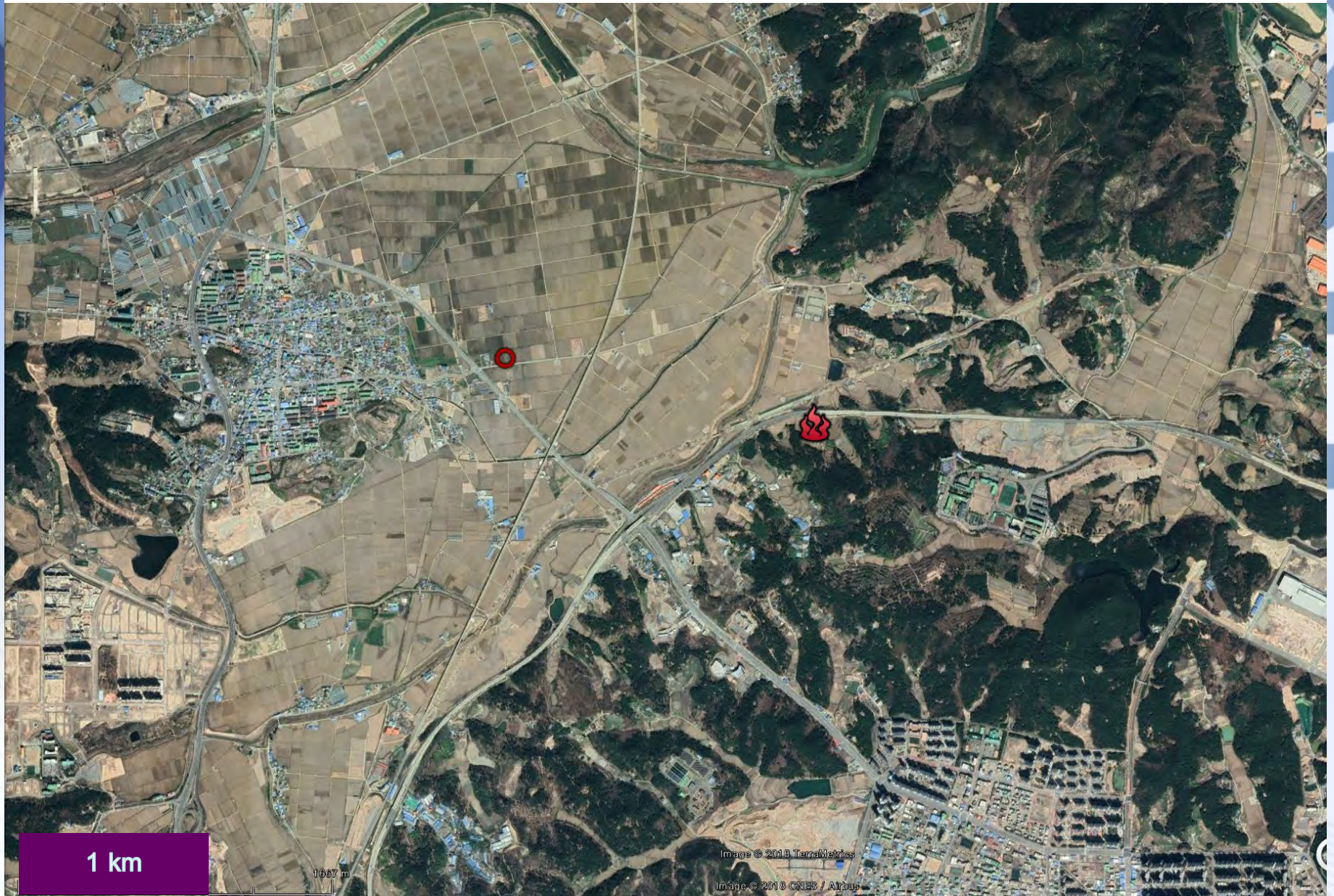
**III . Aftershocks**

**IV . Summary and Discussions**

# Seismicity and Pohang



# M<sub>L</sub> 3.1 earthquake near the Pohang EGS 15 April 2017 (a felt earthquake)



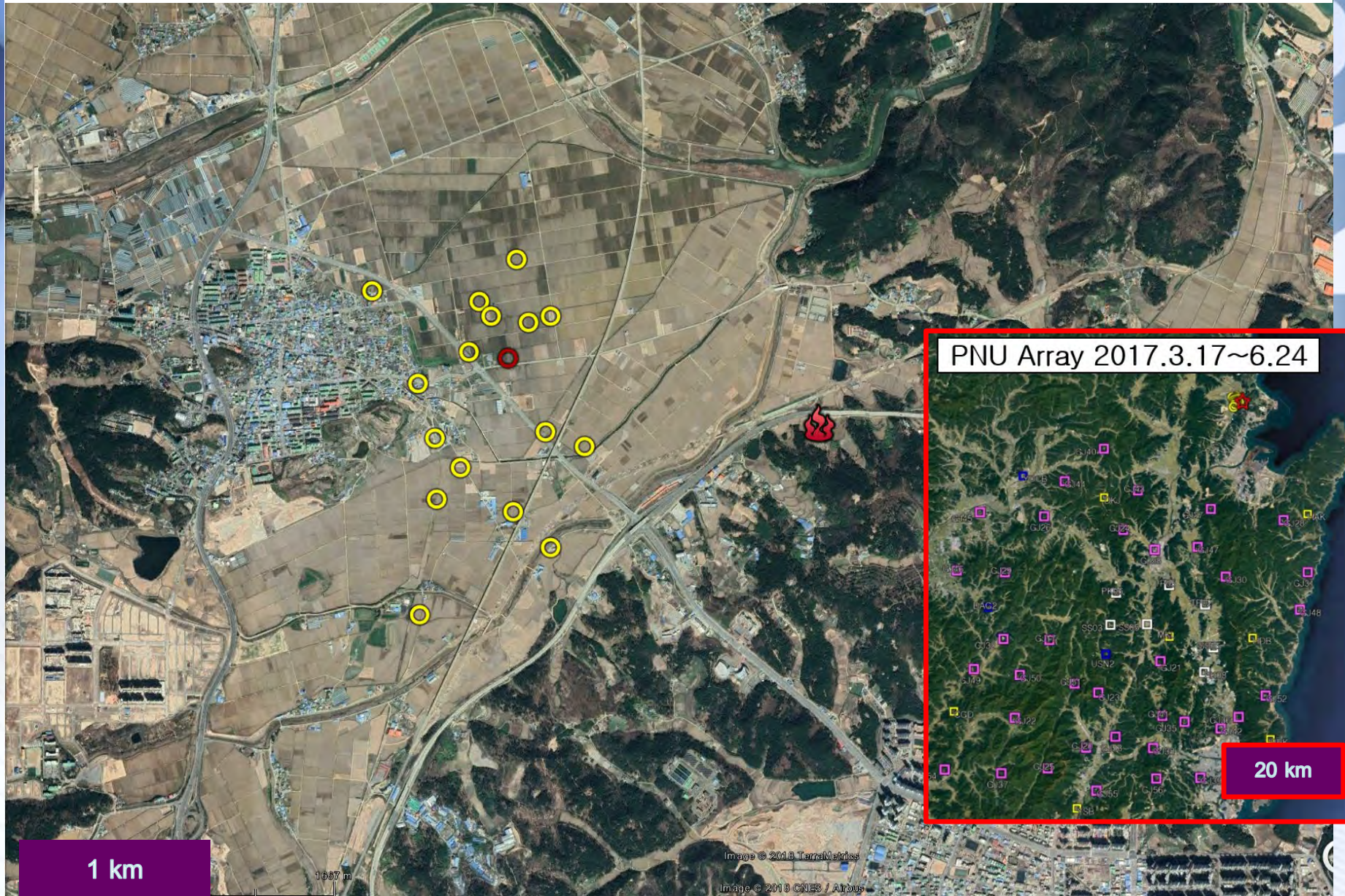
1 km

1667 m

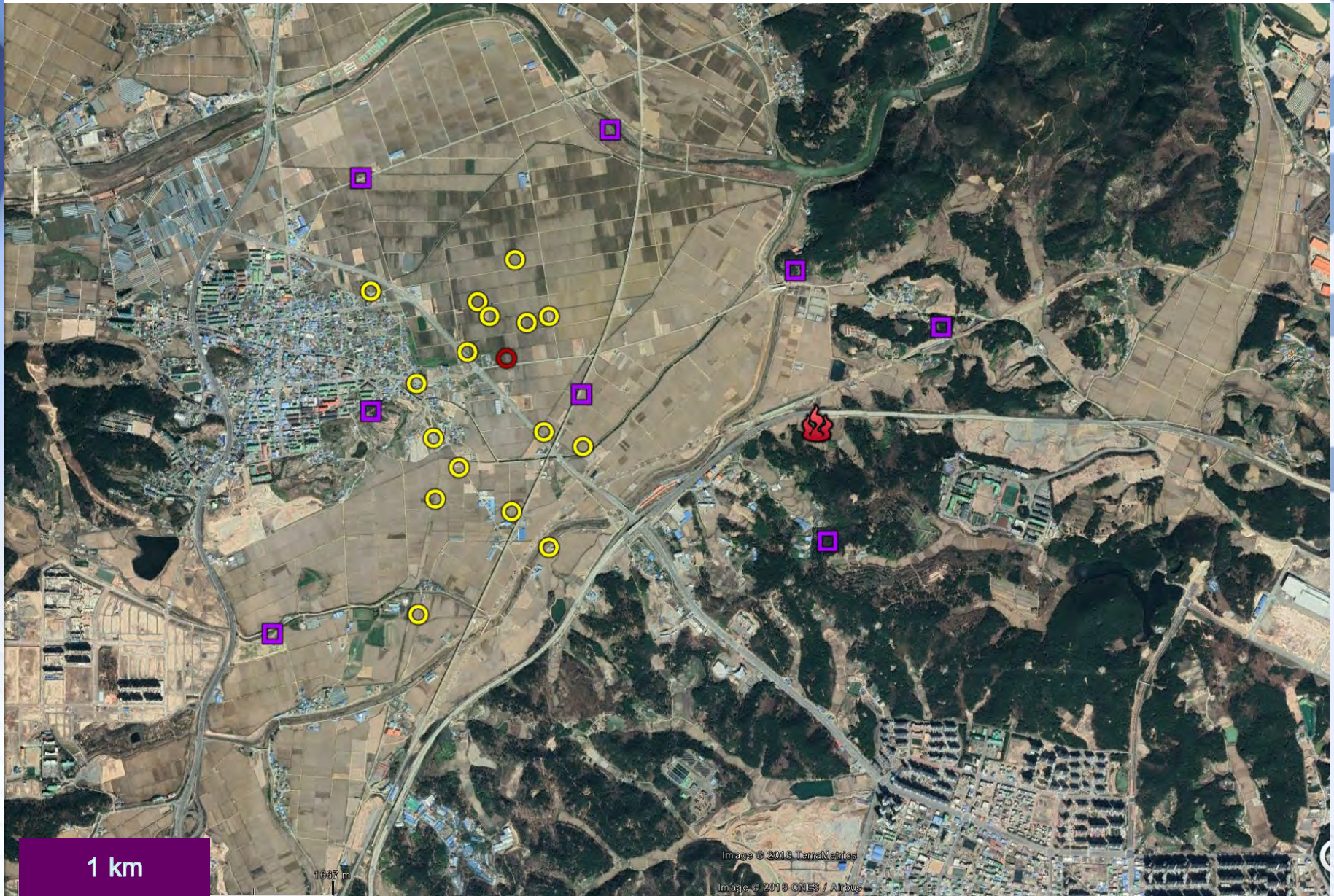
Image © 2013 TerraMetrics

Image © 2016 CNES / Airbus

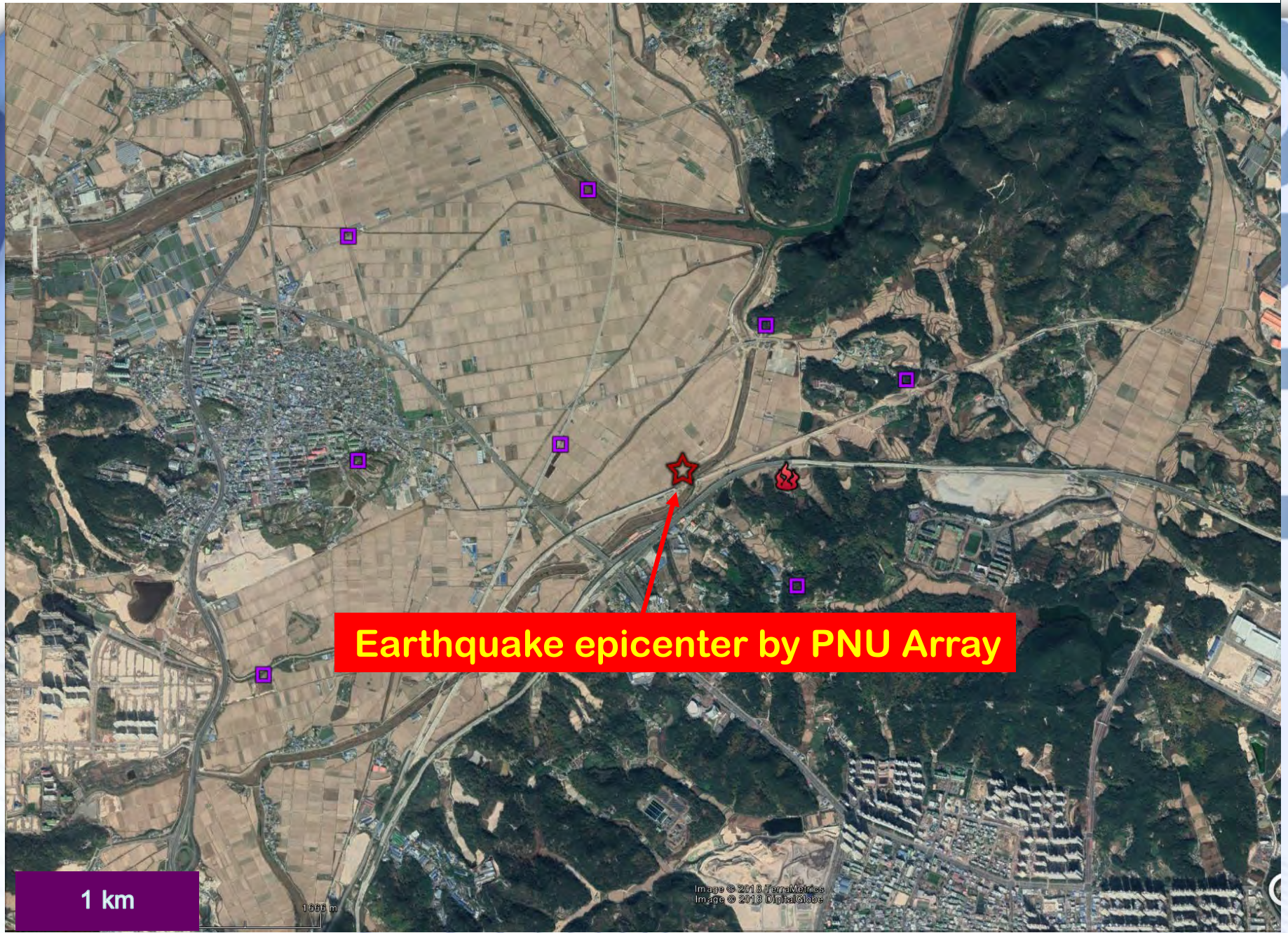
# Micro-earthquakes recorded by PNU seismic array between March 2017 and June 2017



# Temporary seismic stations near the EGS installed on 10 November 2017



# 15 November 2017 $M_L$ 5.4 Pohang Earthquake



Earthquake epicenter by PNU Array

1 km

Image © 2013 TerraMetrics  
Image © 2013 DigitalGlobe

# Waveforms (15 November 2017)

## Foreshock

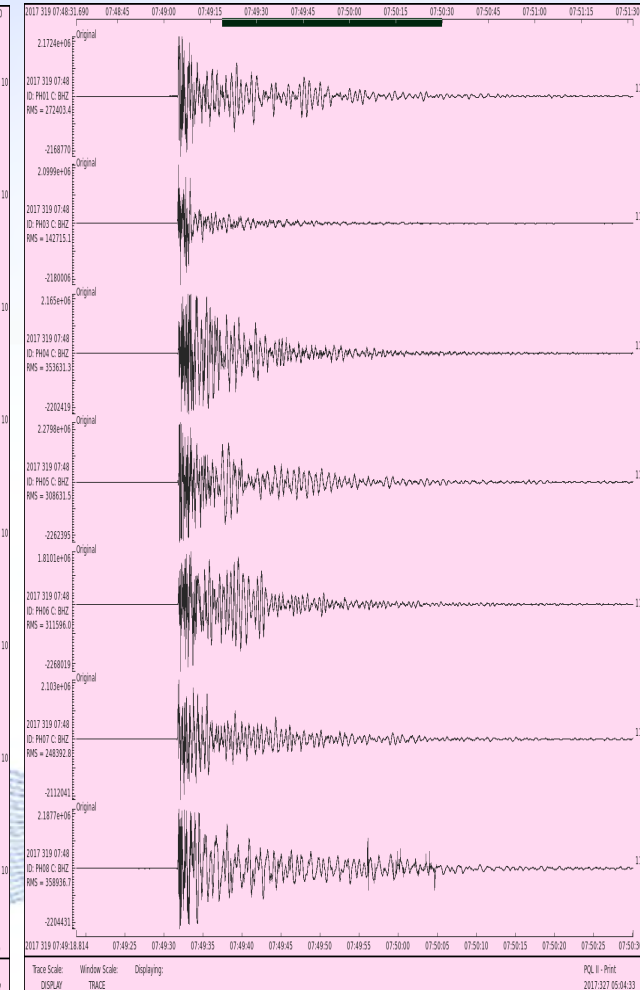
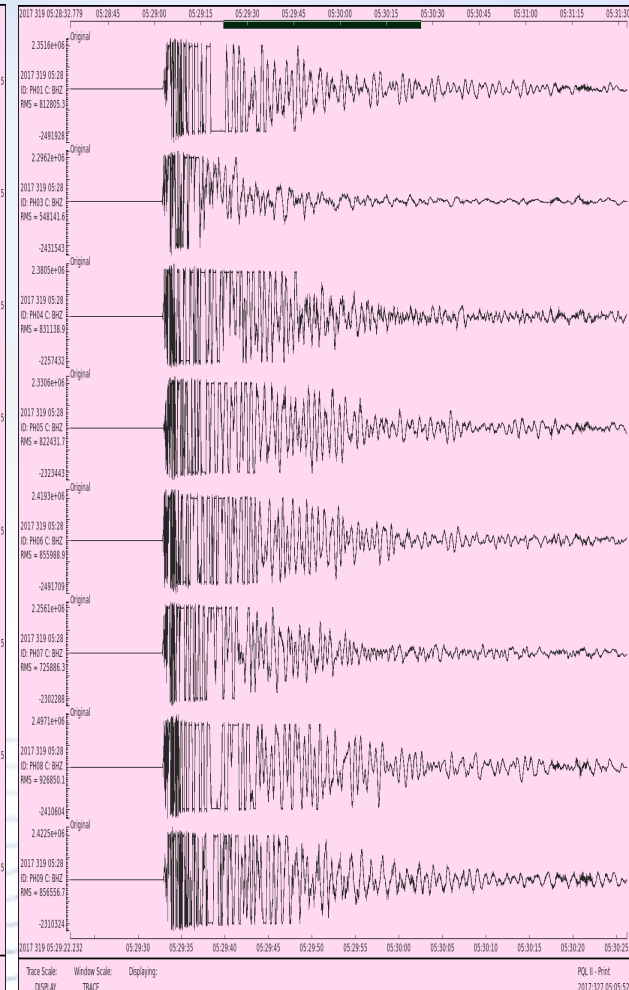
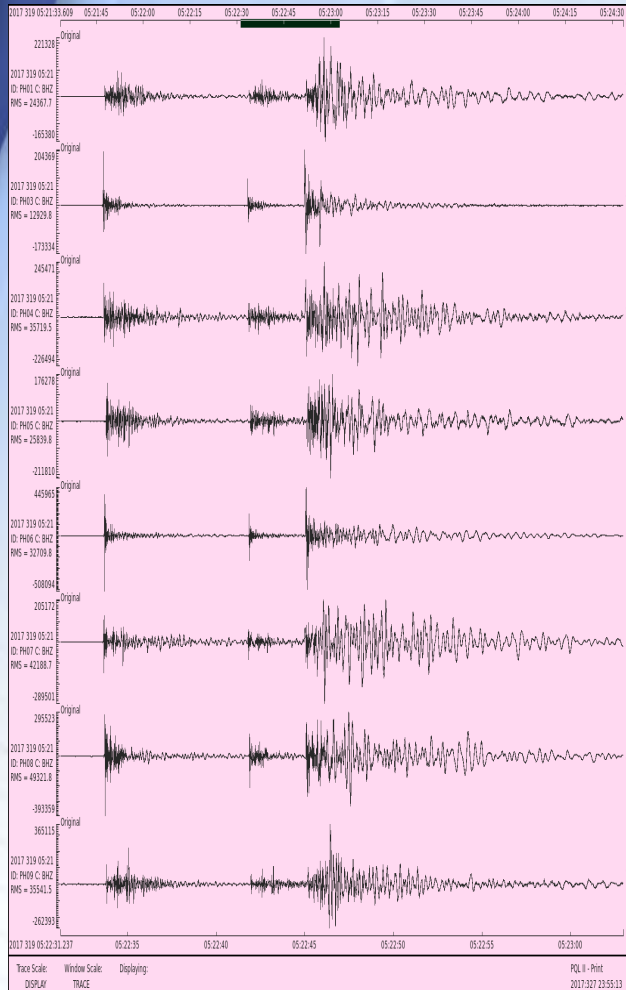
14:22:44  $M_L$  2.6

## Mainshock

14:29:32  $M_L$  5.4

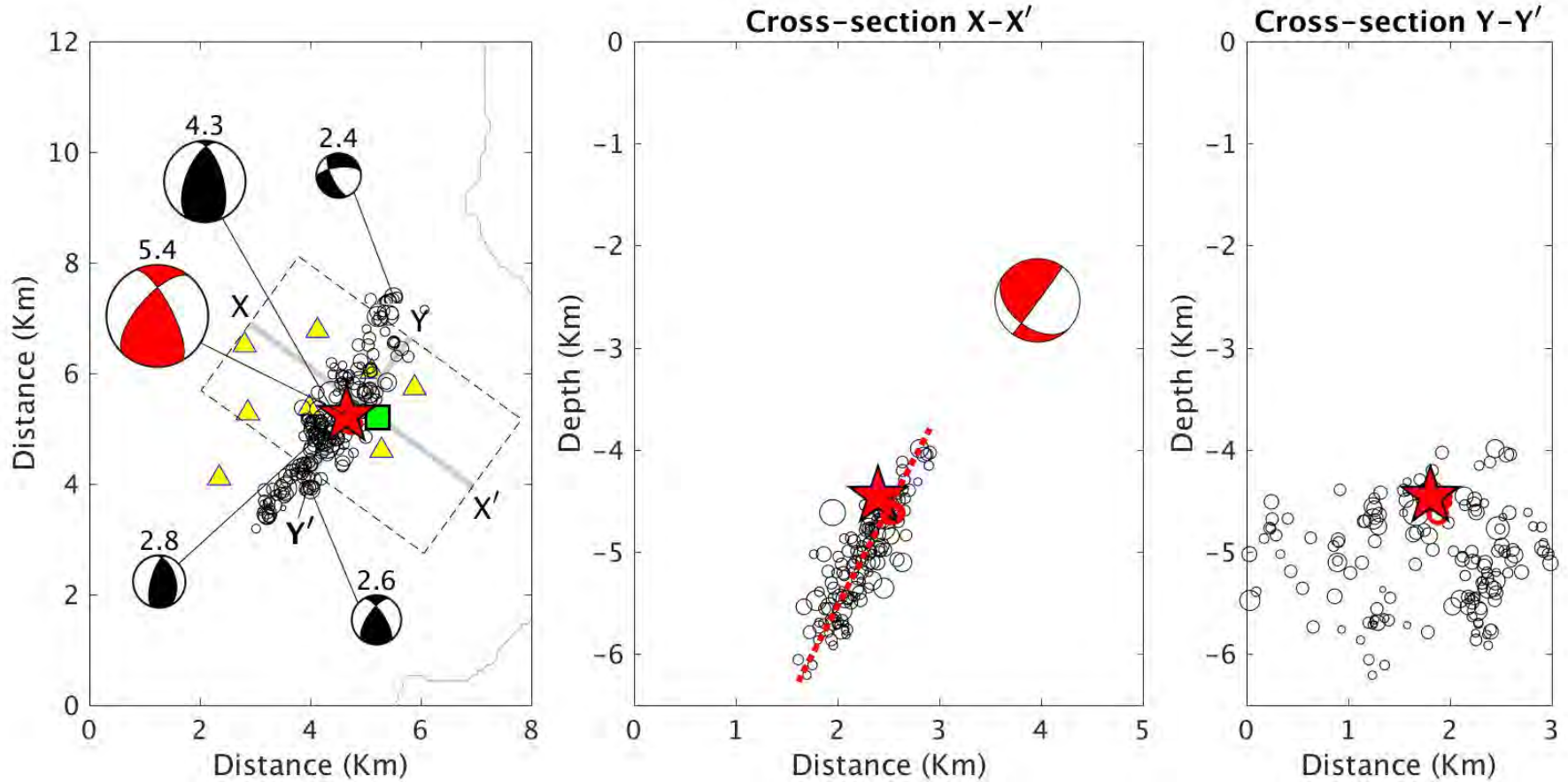
## Aftershock

16:49:31  $M_L$  4.3





# Seismicity in the first 3 hours



**Focal mechanism solutions**

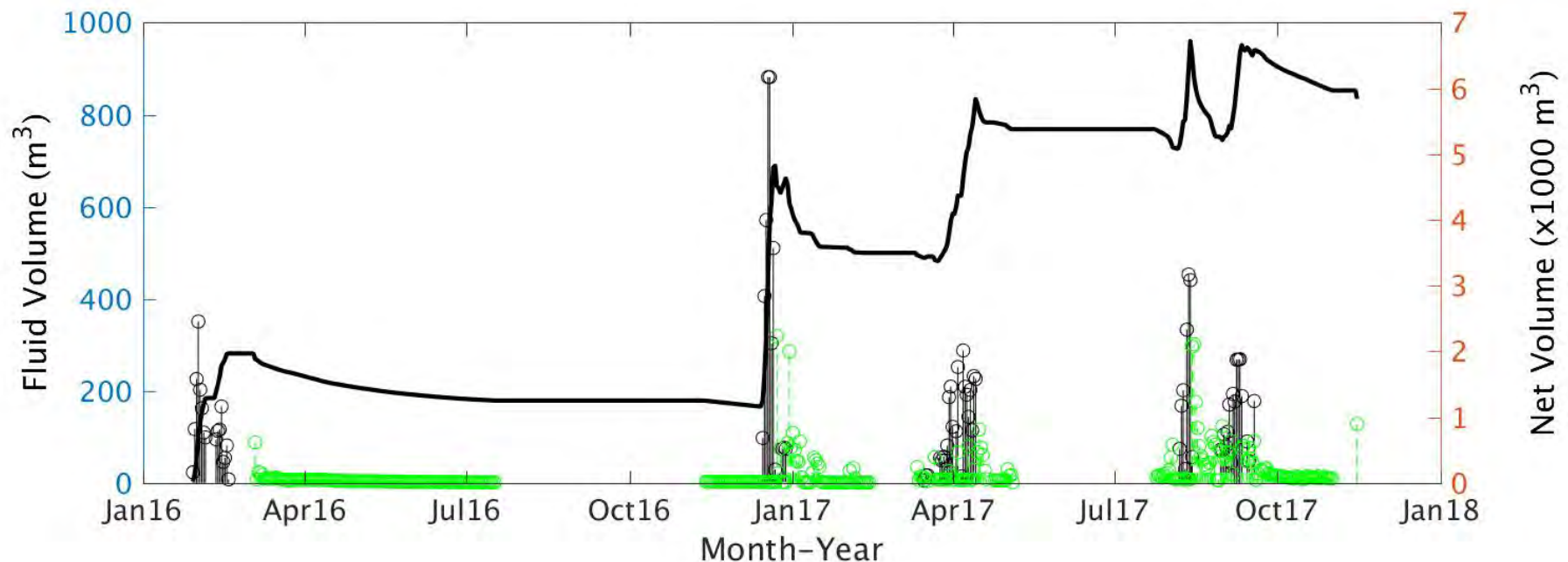
# Seismicity in the first 3 hours

- ❖ Pohang earthquake reactivated previously unknown NE-striking and NW-dipping fault
- ❖ Strike slip with reverse component
- ❖ Second largest and the most damaging event
  - 135 casualties, 30,000 property damages, 297 million USD property loss
  - Shallow hypocentral depth ( $\sim 4.5$  km) in the highly populated area causes large damage



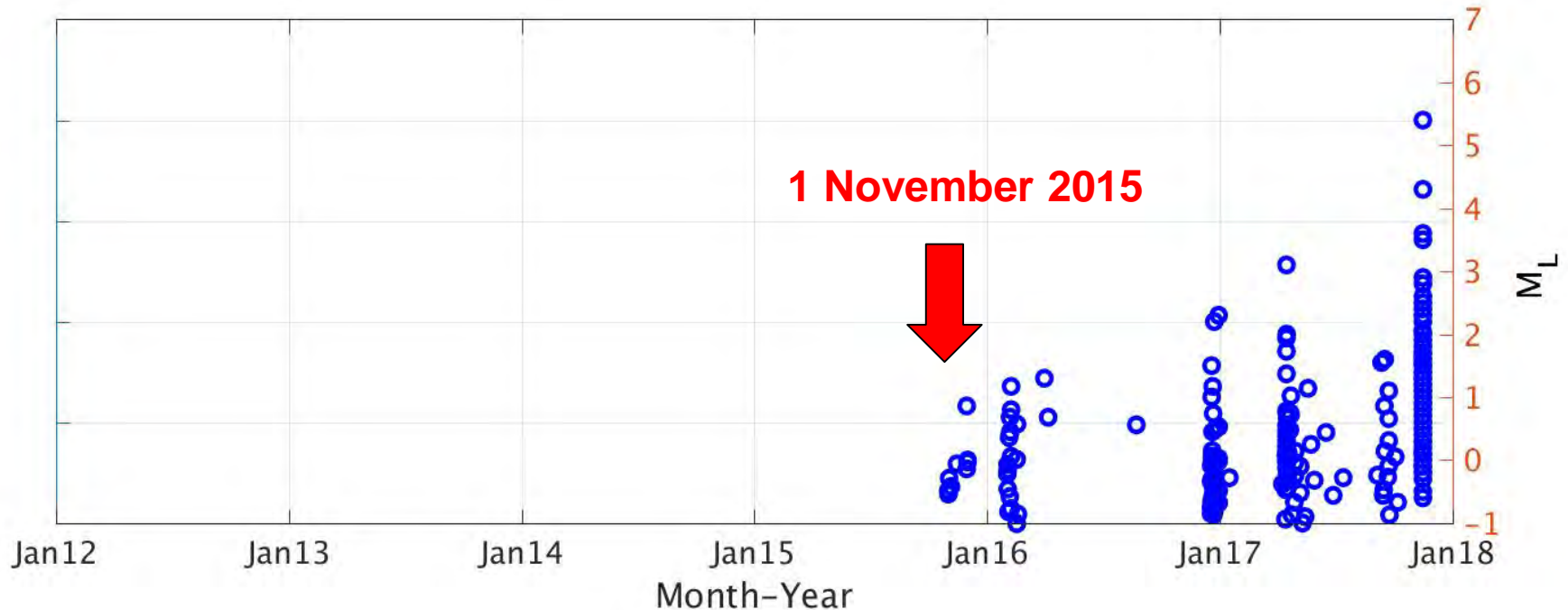
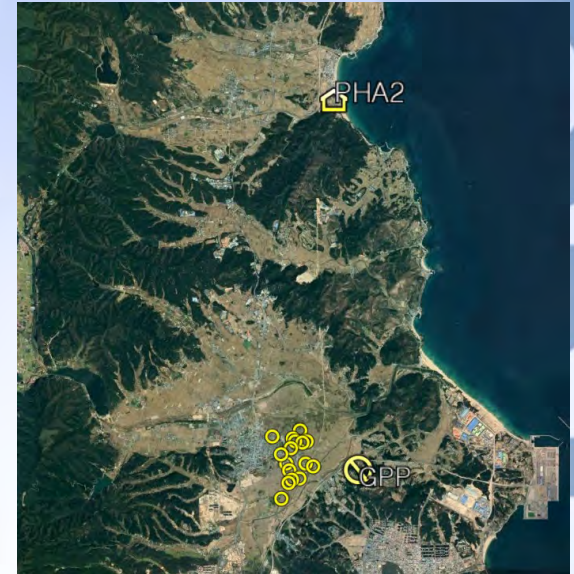
# EGS stimulations

- ❖ Information from the Congressman's office (Sungsoo Kim)
- ❖ First water injection: 29 January 2016
- ❖ Last water injection: 18 September 2017
- ❖ Total amount injected: 12,789 m<sup>3</sup>
- ❖ Bleed-off: 6,957 m<sup>3</sup>
- ❖ Net amount injected: 5,841 m<sup>3</sup>



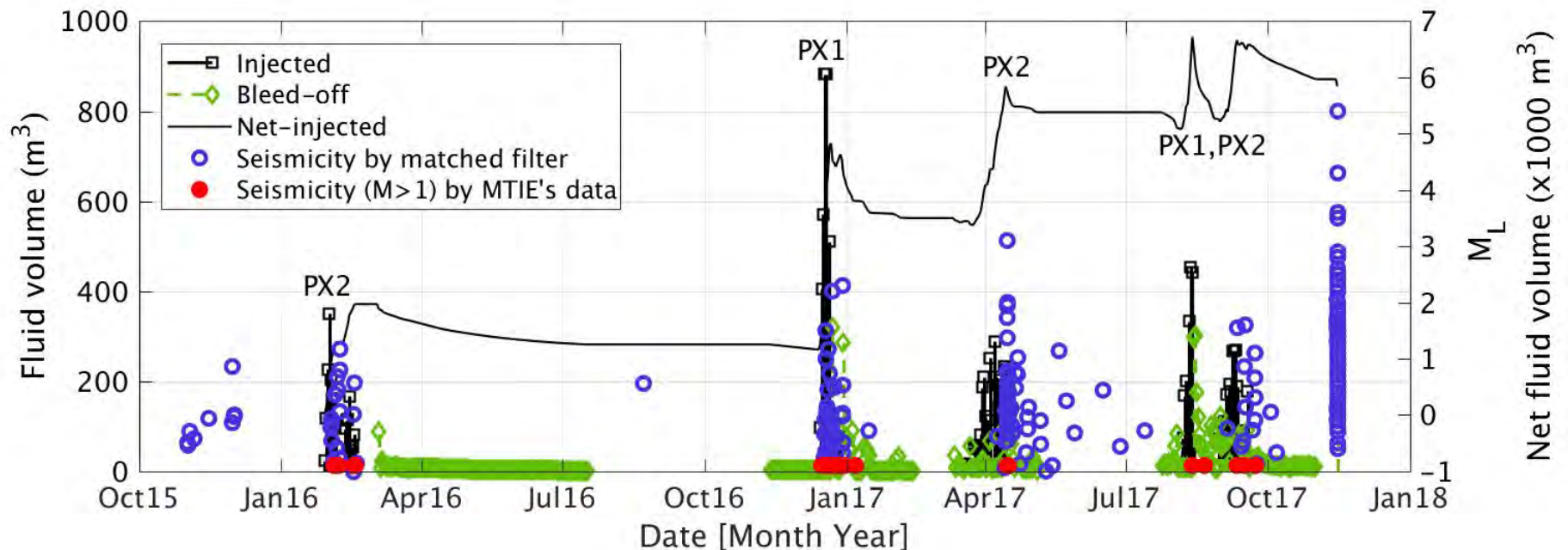
# Unreported Earthquakes

- ❖ **KMA seismic station (PHA2)**
  - Located 10 km north from the Pohang EGS
  - Major instrument upgrade in 2012
  - Applying a matched filter to continuous data from January 2012 to November 2017
- ❖ **Micro-earthquakes have occurred since 1 November 2015**

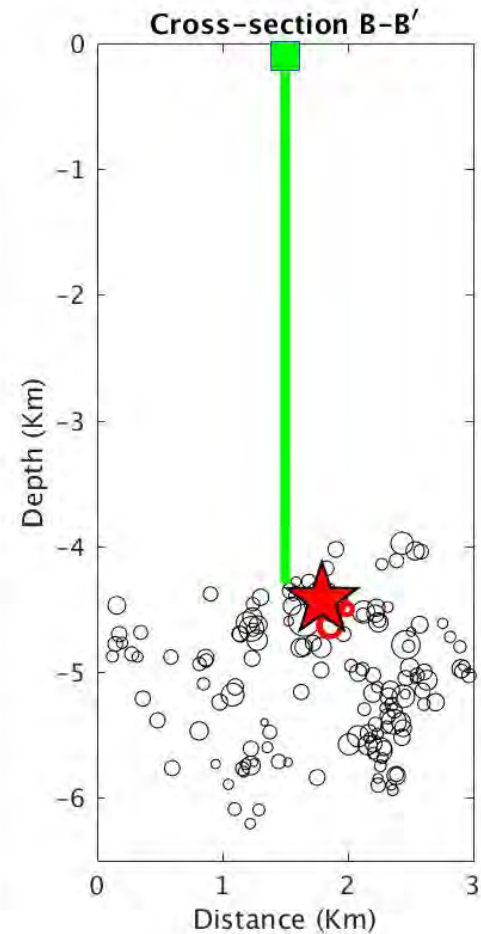
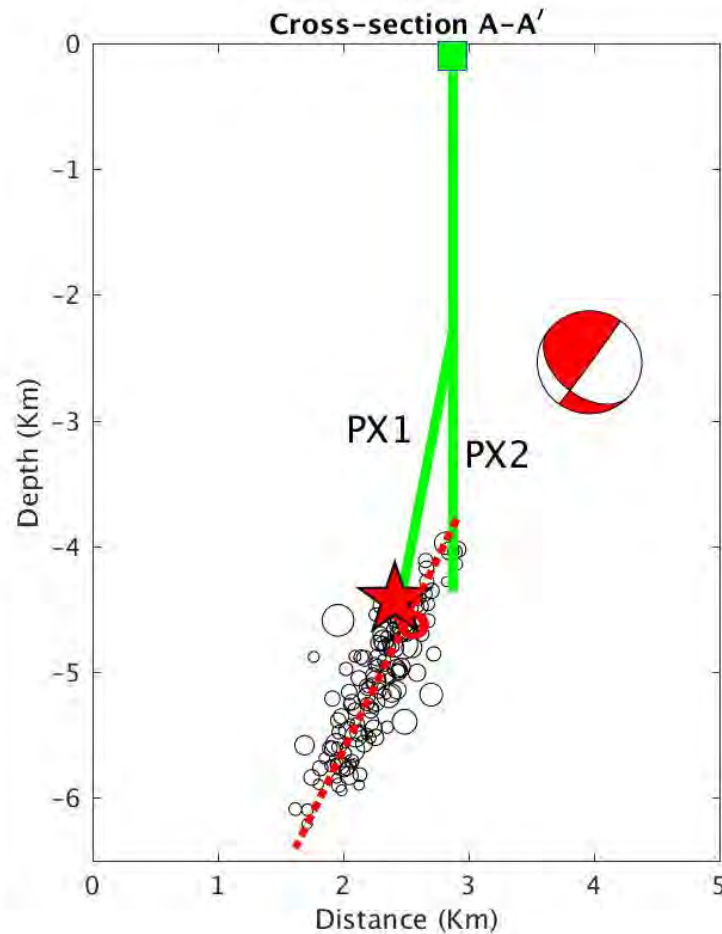
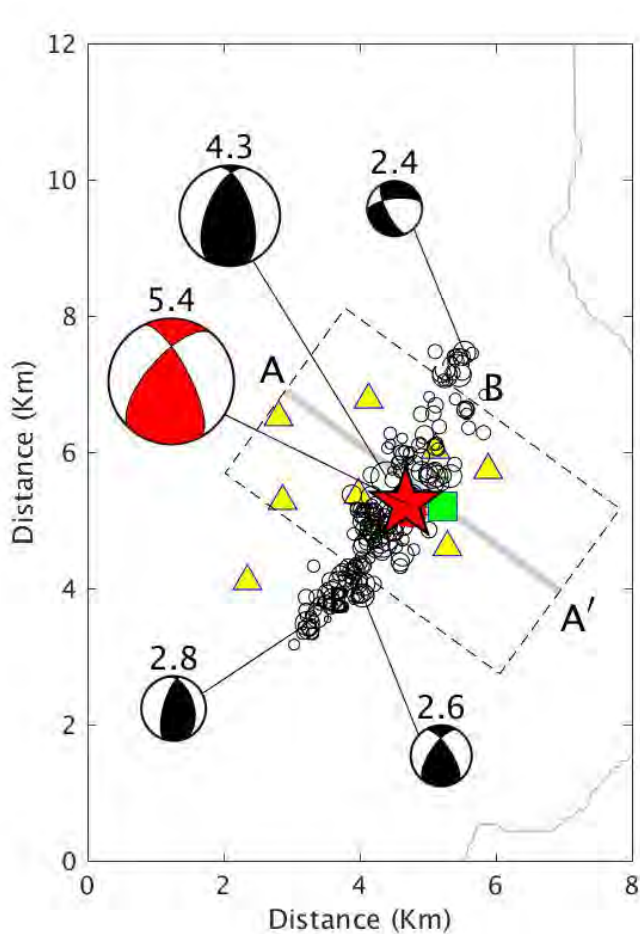


# Fluid injections and earthquakes

- ❖ Temporal correlations between fluid injections and earthquakes
- ❖ Micro-seismicity in November and December 2015?
  - Mud-loss in November and December 2015  
(personal communications with Peter Meier)

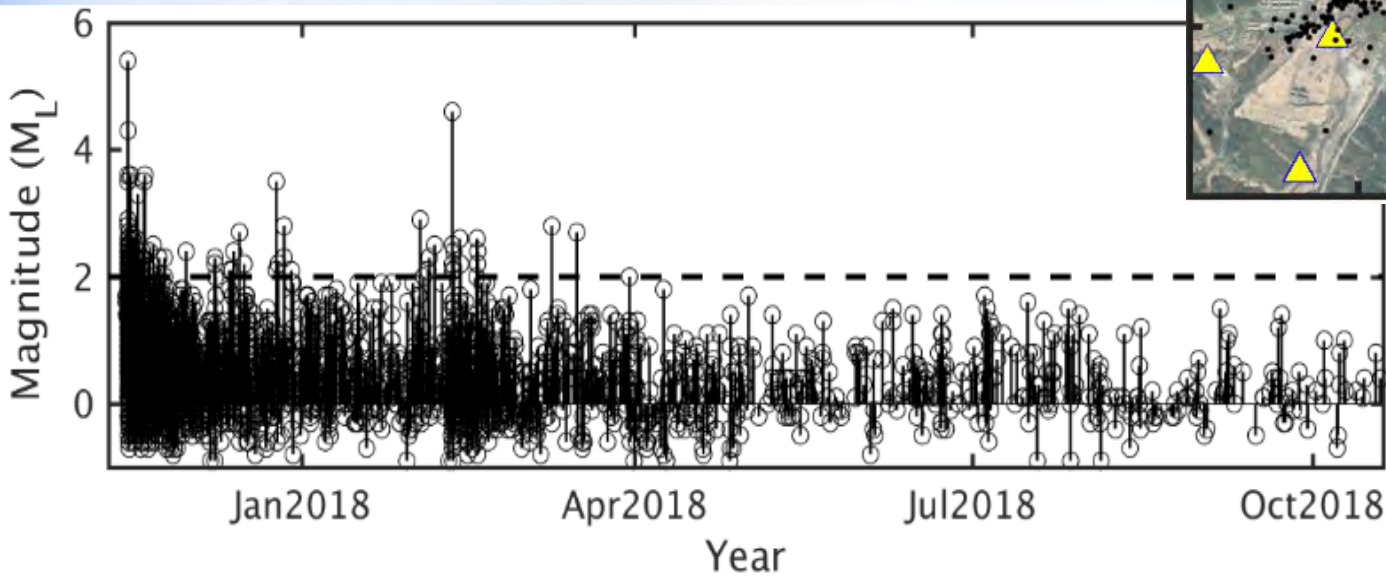
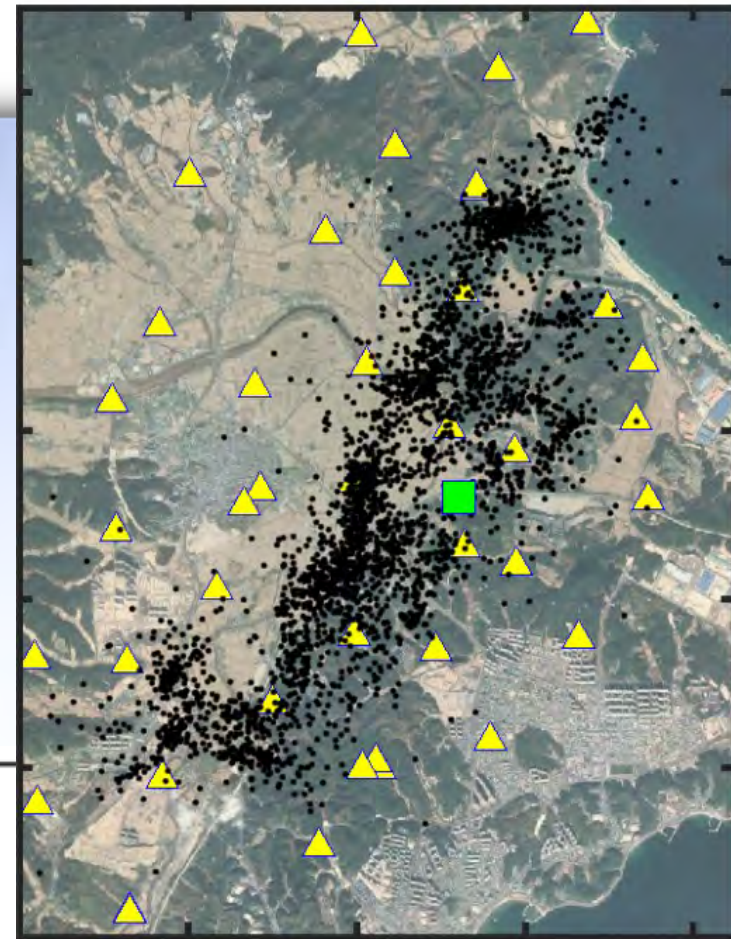


# Spatial correlations among wells, earthquake hypocenters and faults



# Aftershocks

- ❖ **100 earthquakes with  $M \geq 2.0$  (KMA)**
  - Mainshock  $M_L 5.4$  (15 November 2017)
  - Largest aftershock  $M_L 4.6$  (12 February 2018)
- ❖ **More than 3,300 micro-earthquakes**



# Summary

- ❖ **Induced Pohang earthquake ( $M_L$ 5.4) in 15 November 2017**
  - **Second largest and most damaging earthquake in Korea**
- ❖ **Evidences of induced earthquake**
  - **No noticeable seismicity before industrial activity**
  - **Temporal correlation between fluid injection and seismicity**
  - **Spatial correlation between earthquake locations and well bottoms**
  - **Spatial correlation between the reactivated fault and seismicity**
- ❖ **Fluids are directly injected into the fault damage zone**
- ❖ **Poster by Ree et al.**



세계의 미래

PNU로

이  
기  
를  
조  
성  
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고  
자  
라  
게  
요

Pusan National University



감사합니다

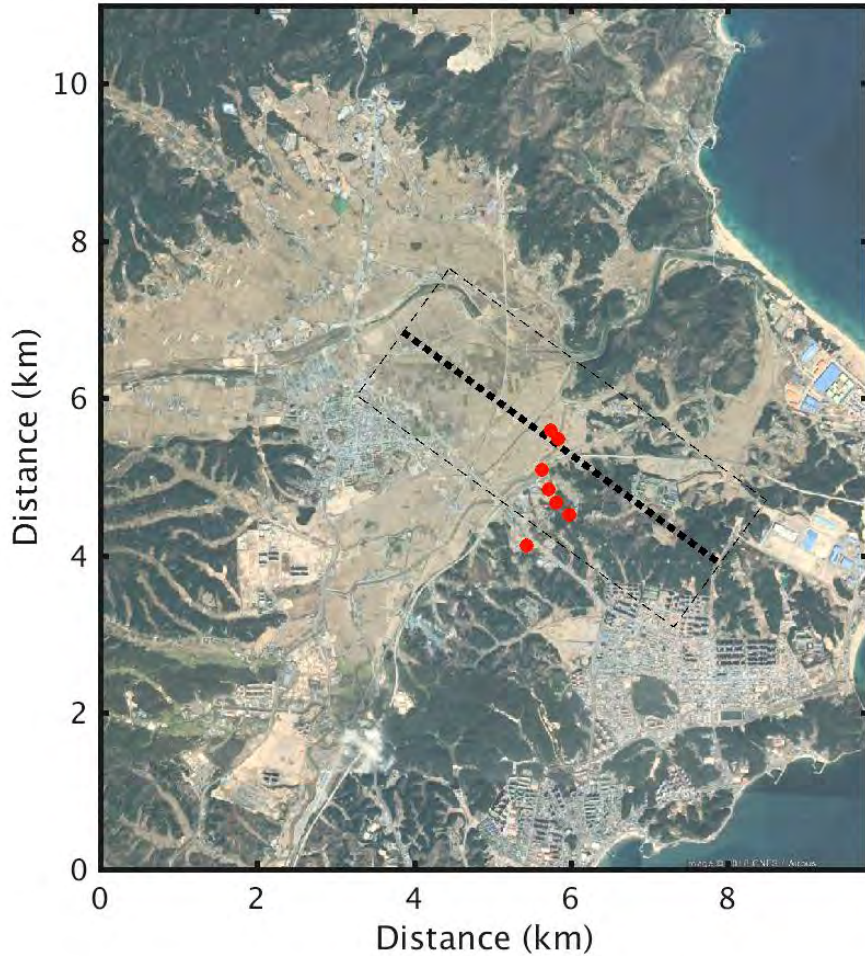
PNU

FUND

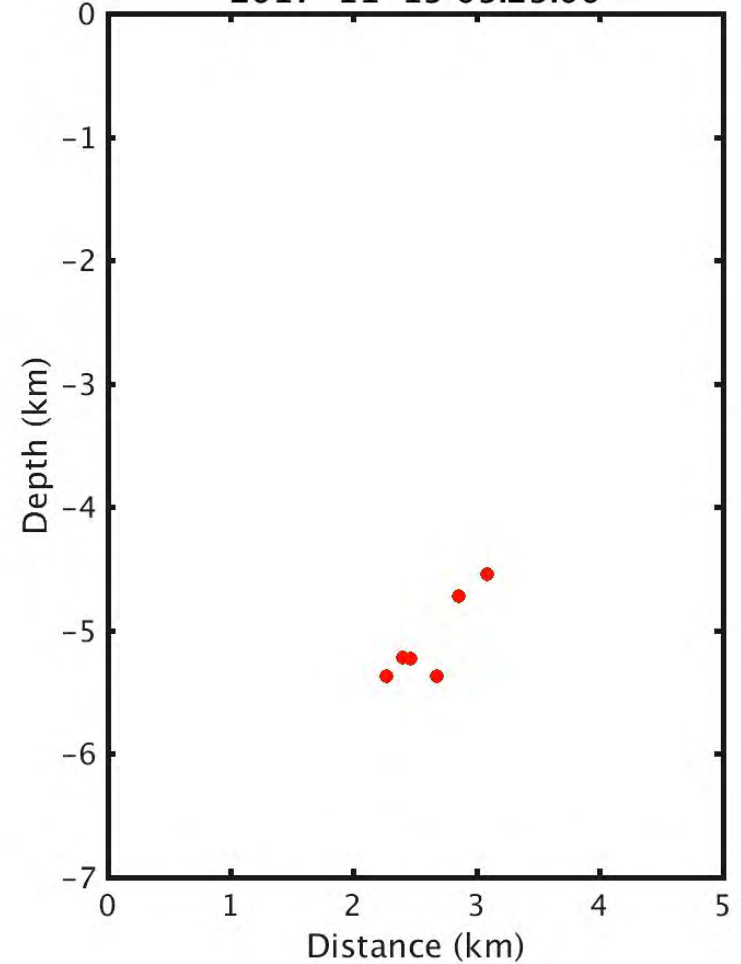


# 포항지역 지진 발생 현황

2017-11-15 05:29:00



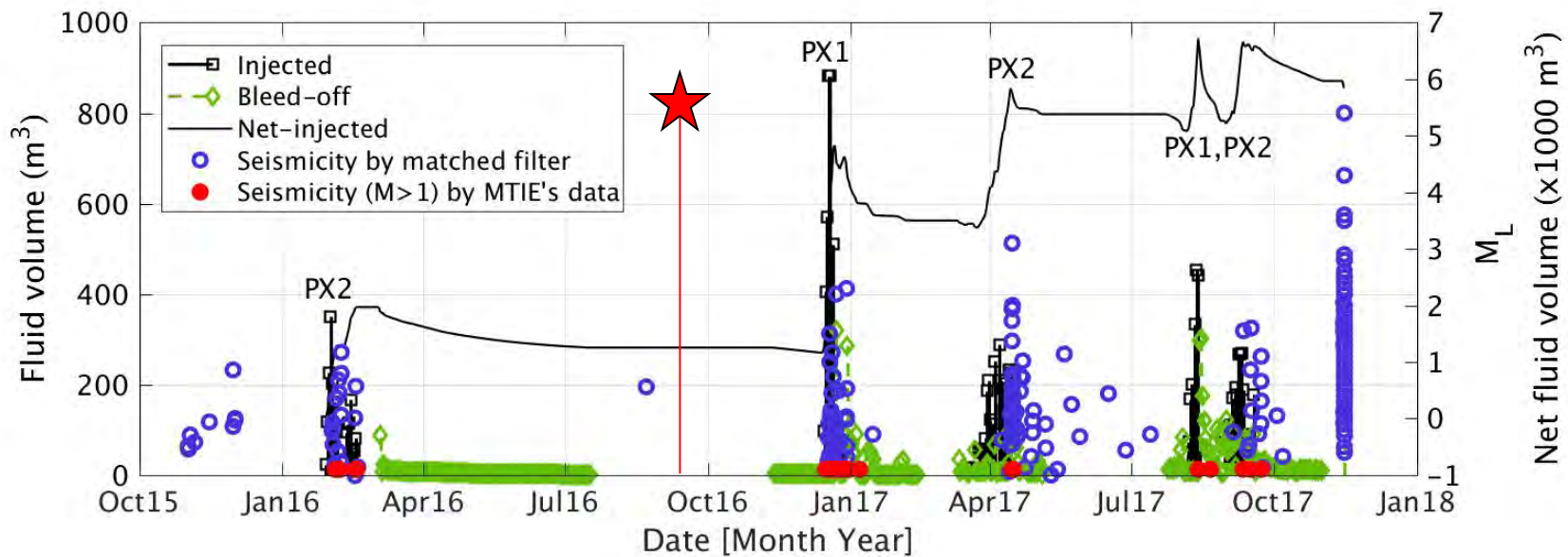
2017-11-15 05:29:00



# Fluid injections and earthquakes

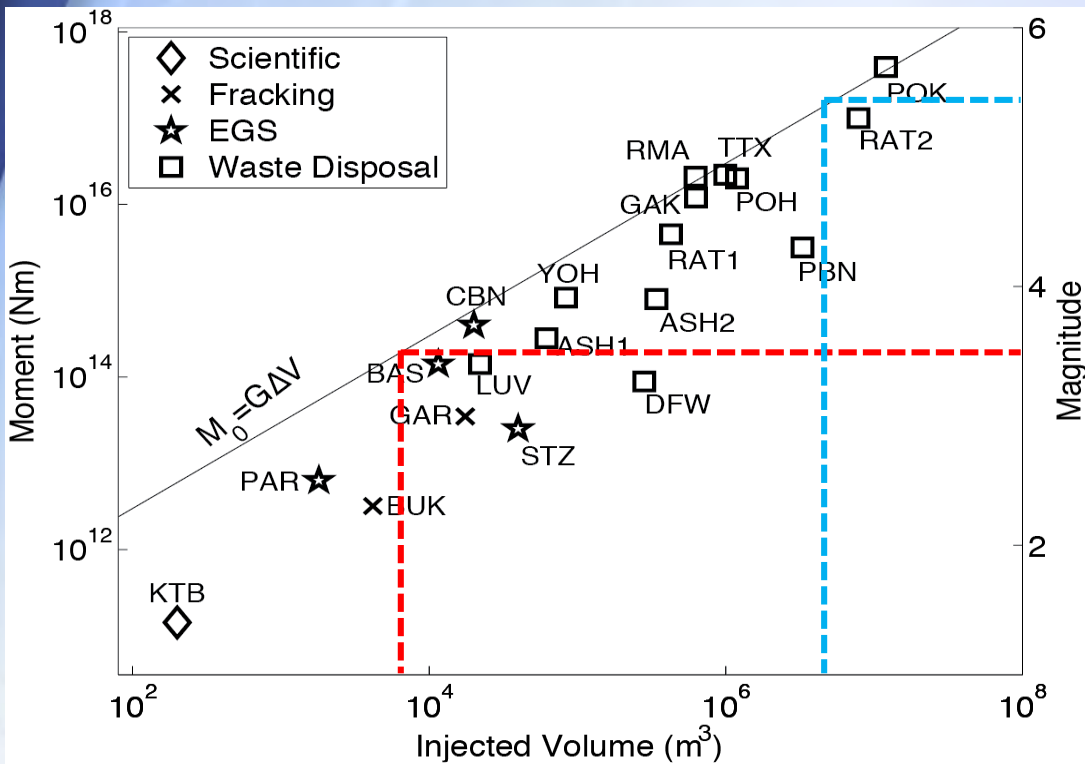
- ❖ Temporal correlations between fluid injections and earthquakes
- ❖ Micro-seismicity in November and December 2015?
  - ❖ Mud-loss in November and December 2015

(personnel communications with Peter Meier)



# Is $M_{\max}$ different for induced seismicity?

❖ Higher injection volumes  $\propto$  possibility of bigger quakes?



(McGarr, 2014)

❖ Net injection at Pohang

EGS:  $5,841 m^3$

$\rightarrow M_{\max} \sim 3.5$

❖ To induce a M 5.4 earthquake, it requires

$4.71 \times 10^6 m^3$

$\rightarrow$  more than 800 times of those injected at Pohang EGS

FUND



유발지진이란?

## Earthquake caused by human's engineering activity

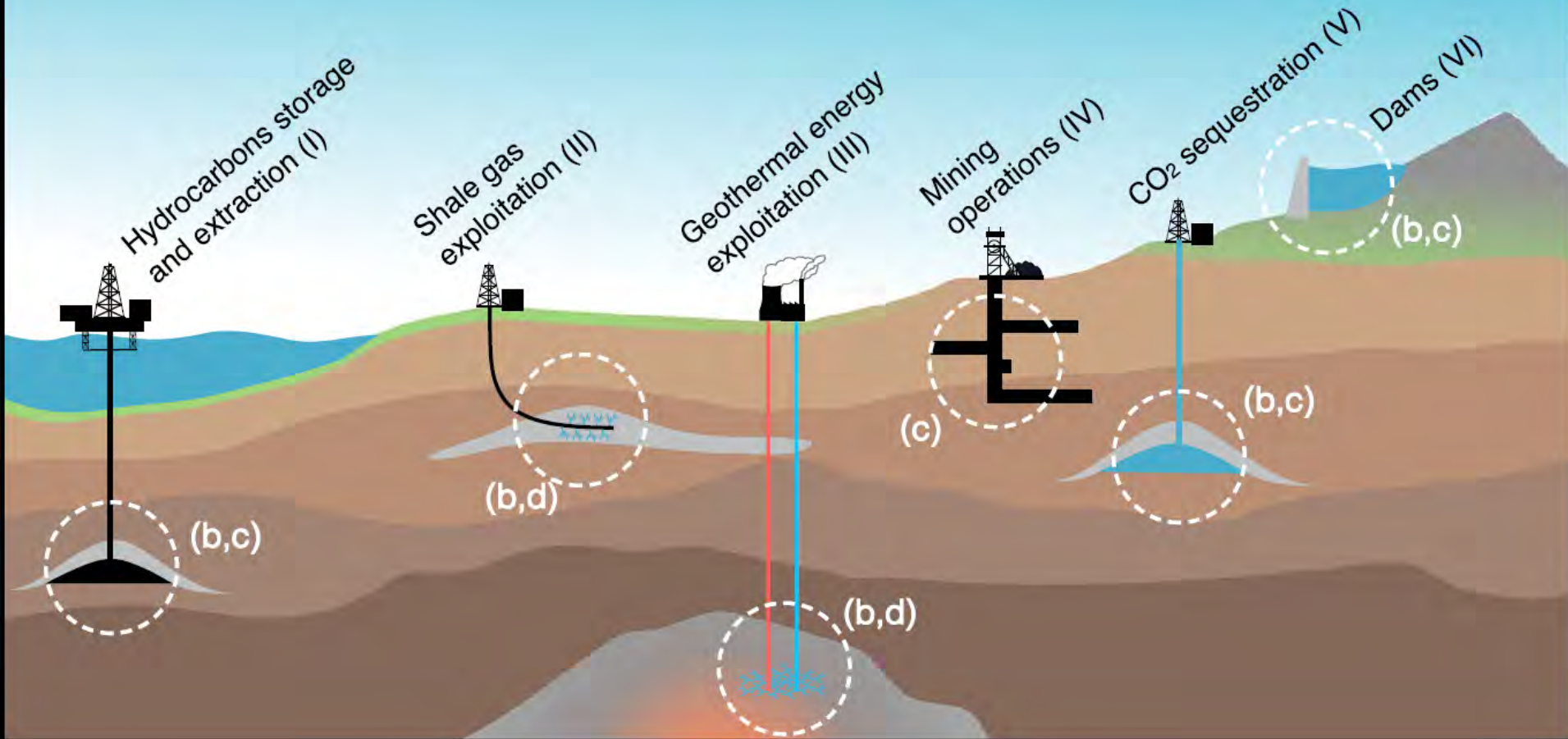
**“not the primary cause of the earthquakes, but just the trigger that acts to release pre-existing stress of tectonic origin”**

**“지진의 일차적 원인이 아니라 기 존재하는 조구조 응력을 해소시키는 방아쇠 역할”**

(Simpson, 1986)

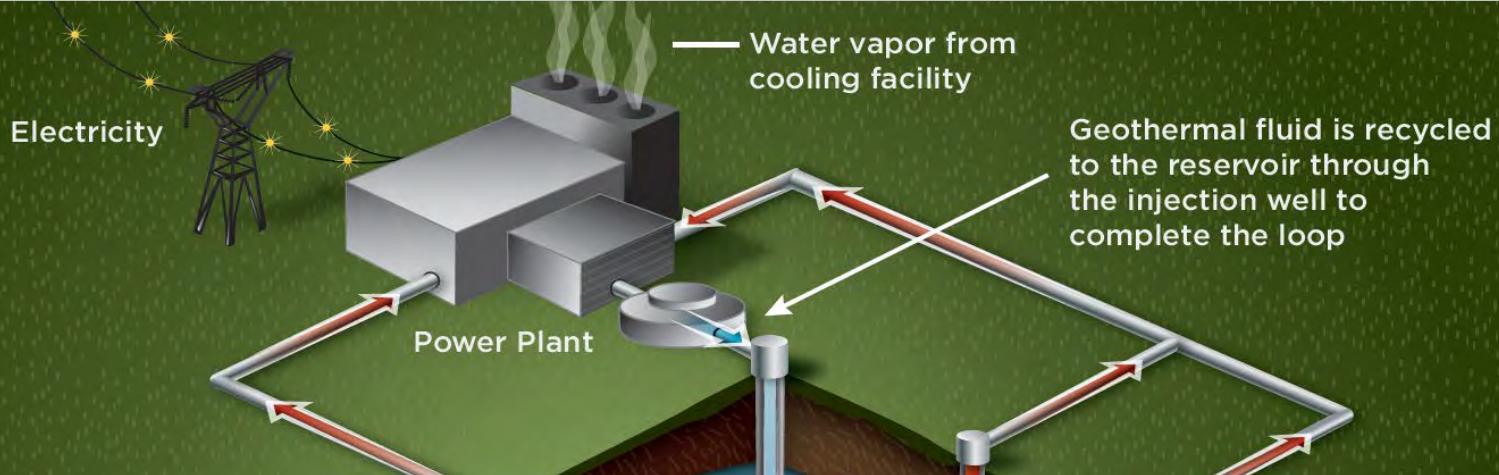
# 유발지진이란?

Main industrial activities which can "induce" or "trigger" seismicity





# 지열발전: 지열 저류층 형성(Enhanced Geothermal System)



- ❖ Identify/characterize a site
- ❖ Create a reservoir
- ❖ Operate the power plant and the reservoir

Geothermal fluid is pumped to the surface through production wells

Injected geothermal fluid enhances the permeability of the rock

# Outlines

- ❖ 지열발전소 건설 이전에 흥해지역에서는 지진이 발생하지  
않음
  - (시추공 완성과 함께 지진발생 시작)
- ❖ 물 주입 시기와 (미소)지진발생 시기 일치
- ❖ 주입정/생산정의 위치/깊이와 전진/본진의 발생  
위치/깊이 일치
- ❖ 지하단층의 위치와 주입정/생산정의 위치 일치
- ❖ 지하단층에 고압의 유체를 직접 주입

# 부산대학교 이동식 지진관측망: 경주지역 3차원 지하구조 연구

- ▶ 2017.03.17부터 2017.11.05까지 3차원 지하구조 연구를 위한 이동식 지진관측망 운영 (약 150개소)

PNU Phase 1: '17.03.17~05.09

PNU Phase 2: '17.05.05~06.24

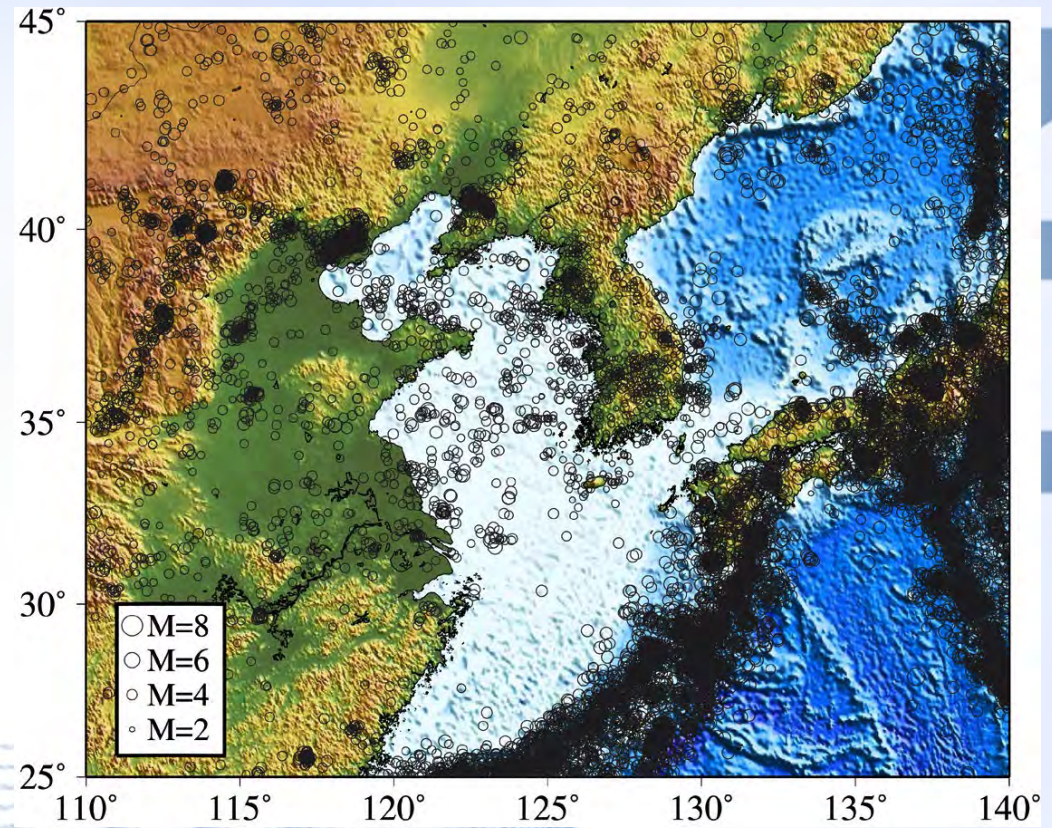
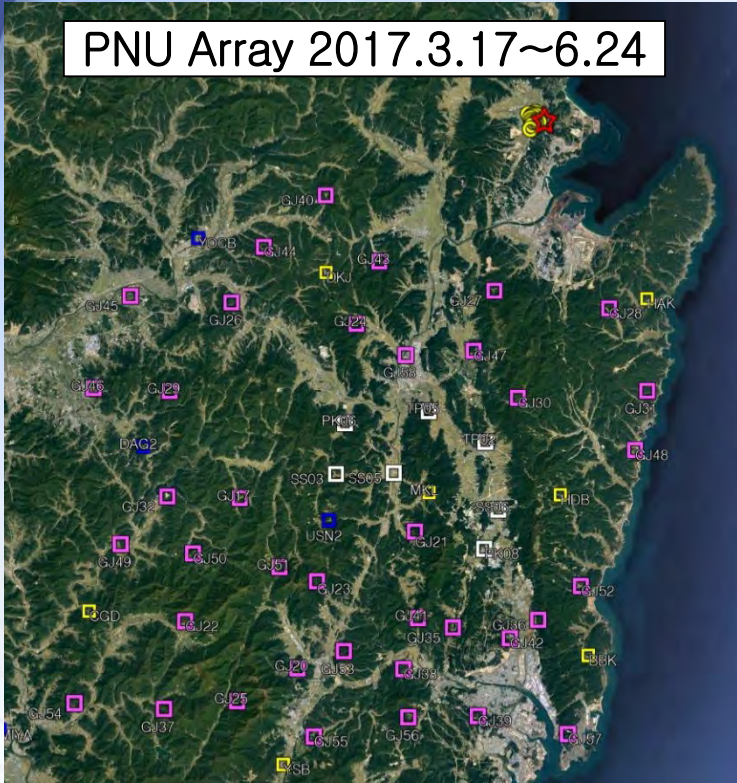
PNU Phase 3: '17.06.23~08.25

PNU Phase 4: '17.08.22~10.01

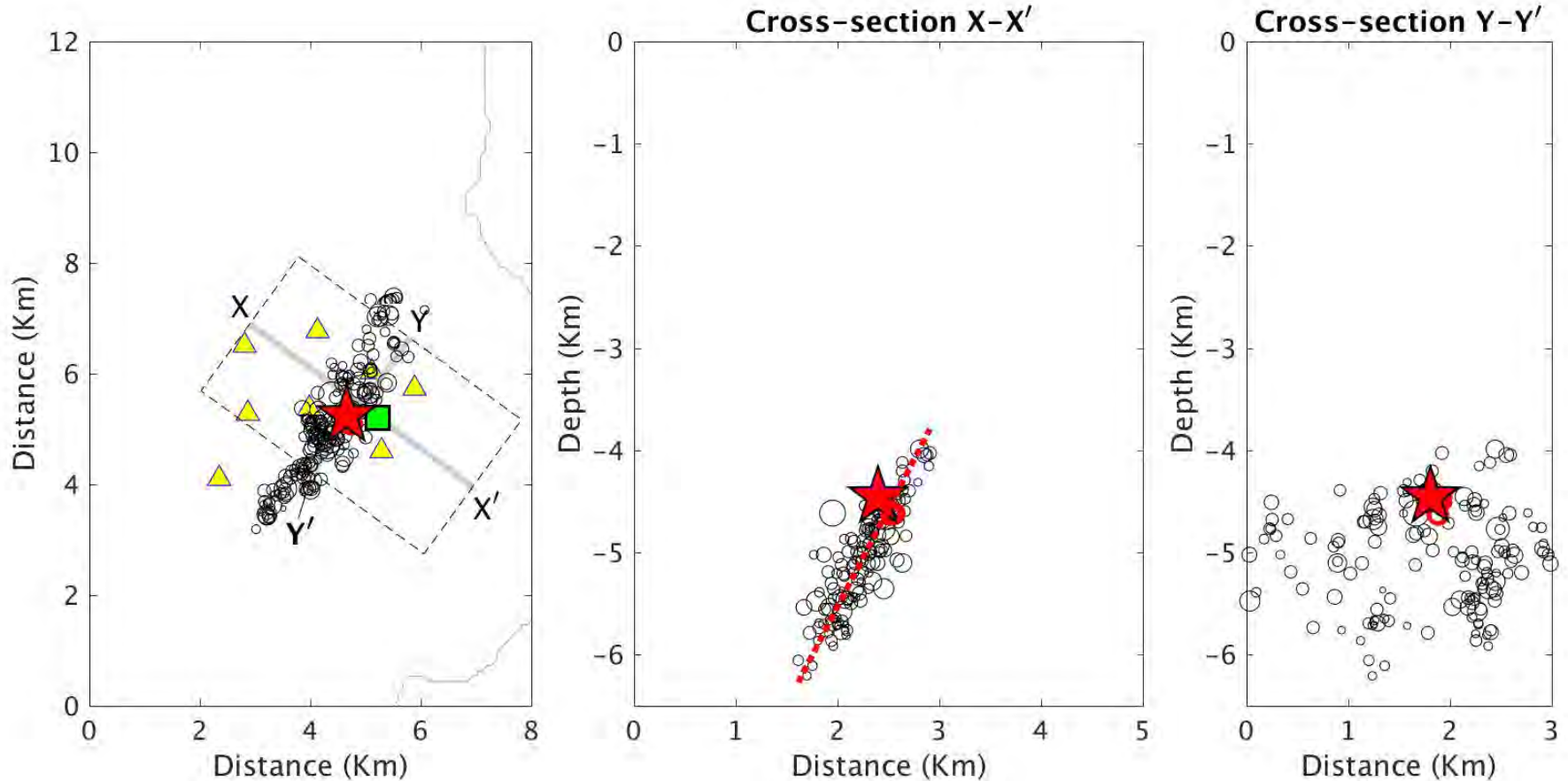
PNU Phase 5: '17.09.29~11.05



PNU Array 2017.3.17~6.24



# Seismicity in the first 3 hours

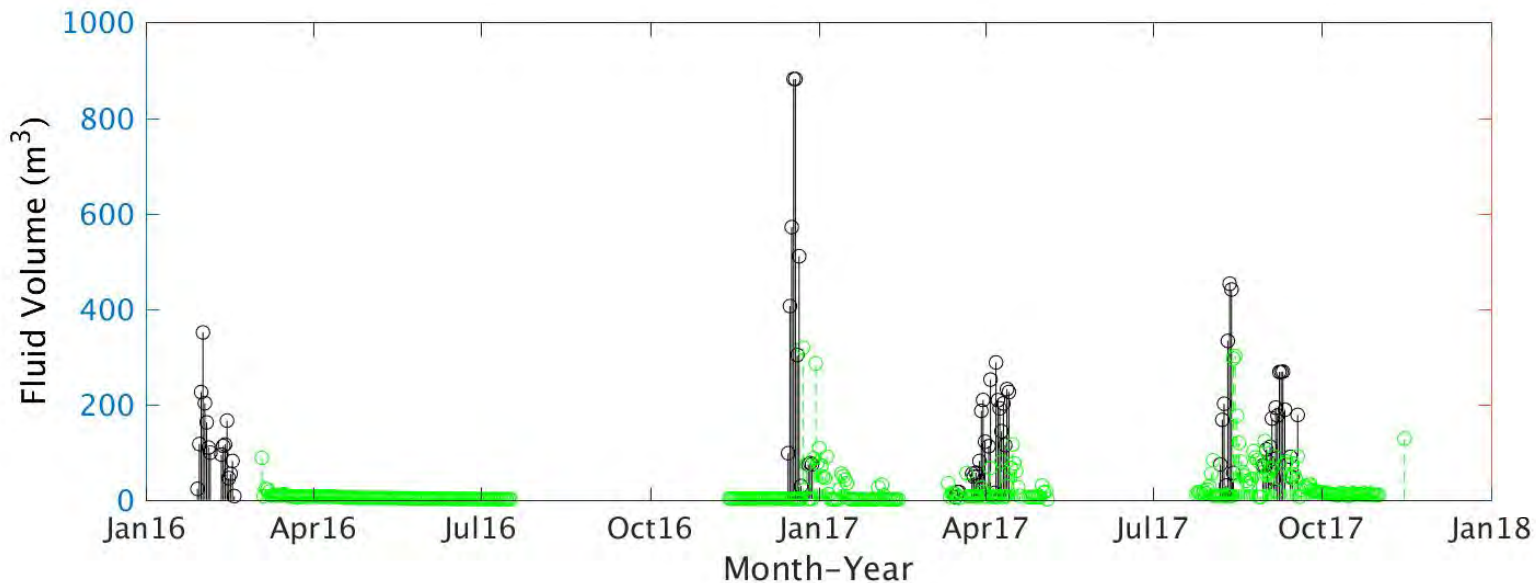


**Fault plane inferred from the seismicity**



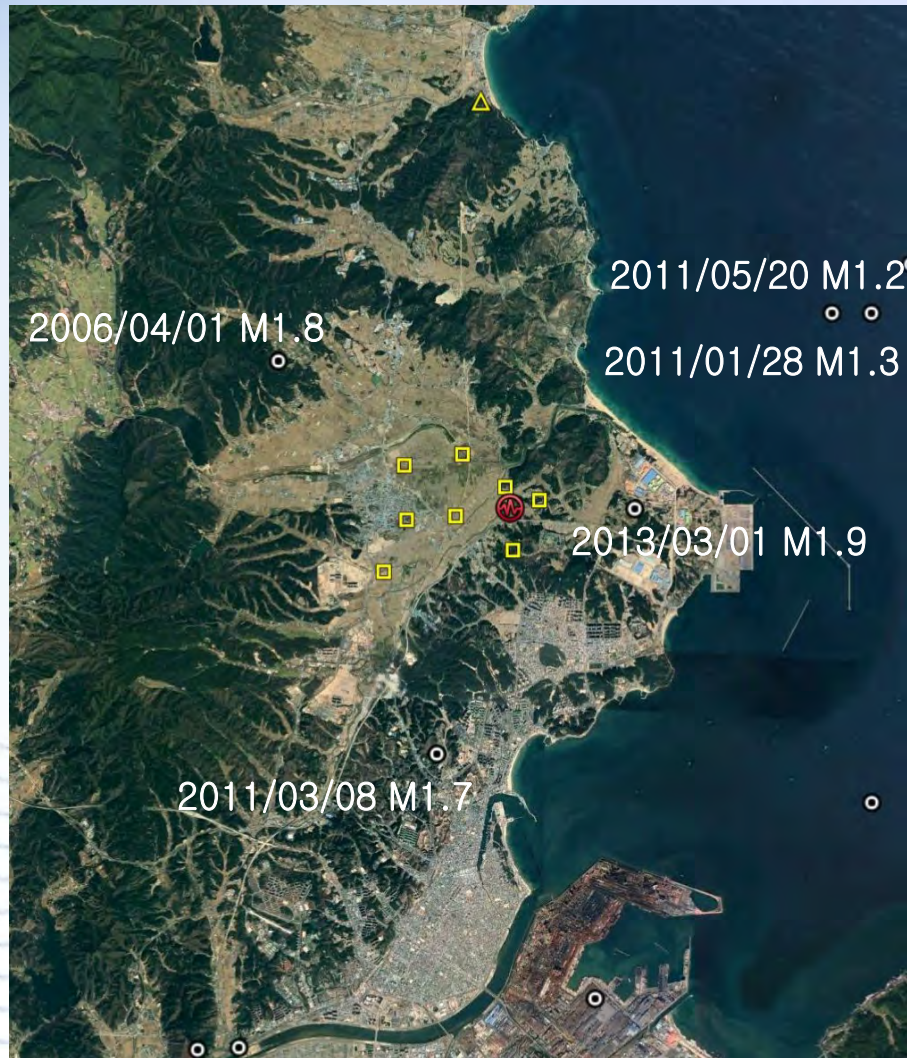
# EGS stimulations

- Information from the Congressman's office (Sungsoo Kim)
- First water injection: 2016. 1. 29, Last water injection: 2017. 9. 18
- Total amount injected: 12,789 m<sup>3</sup> , Bleed-off: 6,957 m<sup>3</sup>



# 포항지진 이전 지진 이력

- ❖ 기상청 자료: 1978년부터 2015년 10월까지 지열발전소 주변 반경 10 km 내에서는 규모 2.0 이상 지진이 발생하지 않음



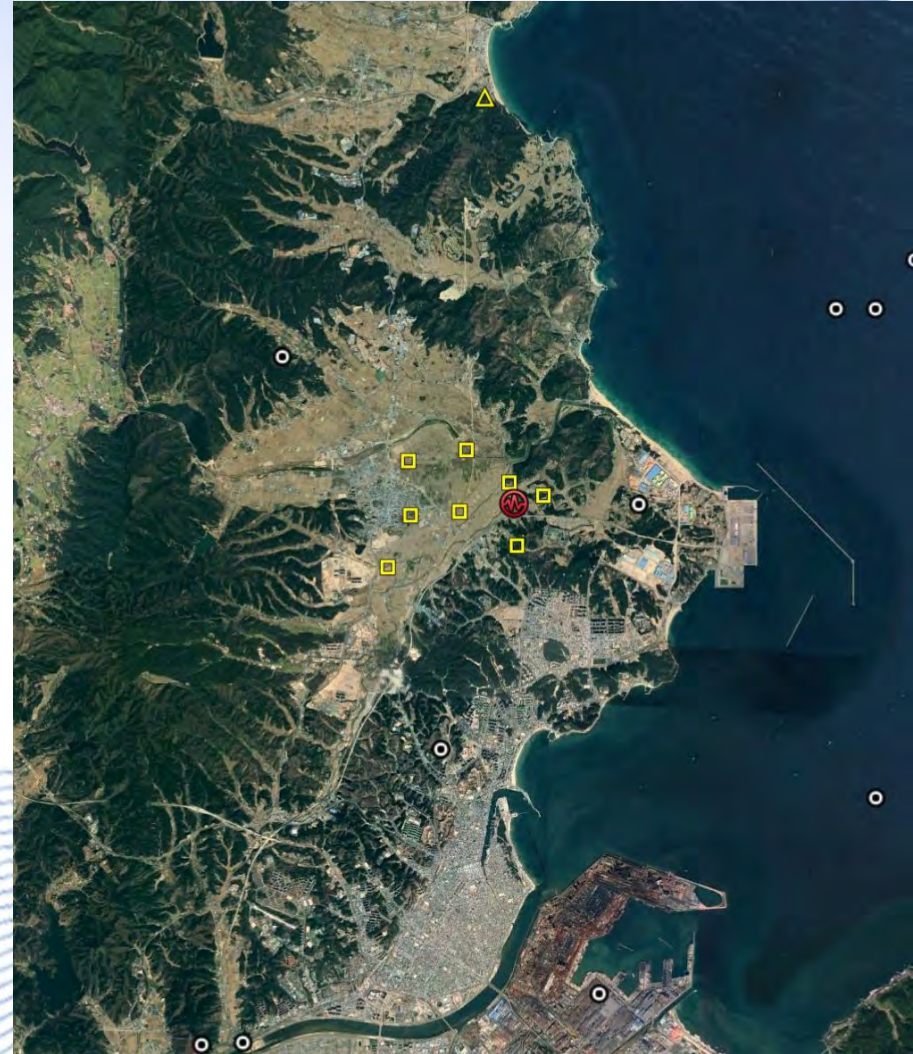


# 지열발전소 인공저류층 형성과 지진

❖ 1978년부터 2015년 10월까지 지열발전소 주변 반경 10 km 내에서는 규모 2.0 이상 지진이 발생하지 않음

❖ 포항지진 발생 이전 2016-2017 동안 지진 11회 발생 (기상청)

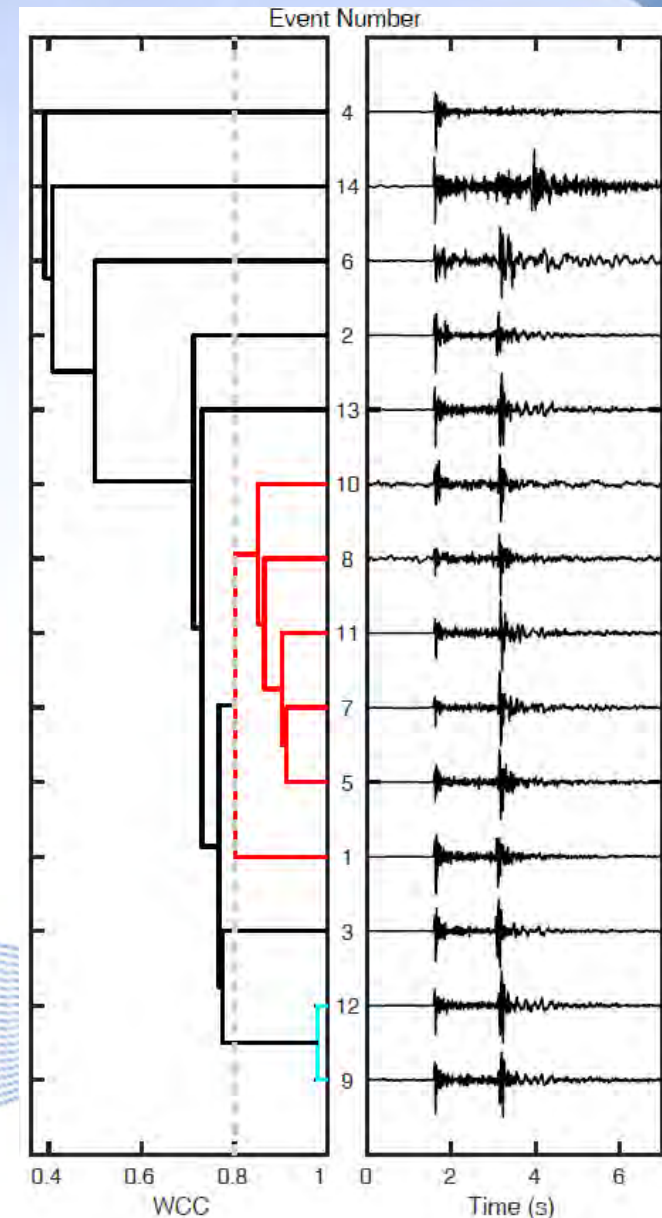
- 2016/03/31 12:58:14  $M_L$  1.3
- 2016/12/18 22:55:51  $M_L$  1.5
- 2016/12/20 03:43:44  $M_L$  1.0
- 2016/12/23 05:31:32  $M_L$  2.2
- 2016/12/29 21:32:25  $M_L$  2.3
- 2017/04/15 11:31:13  $M_L$  3.1
- 2017/04/15 17:16:47  $M_L$  2.0
- 2017/09/11 16:19:24  $M_L$  1.5
- 2017/09/16 17:55:55  $M_L$  1.6
- 2017/09/22 23:27:21  $M_L$  1.1
- 2017/09/23 03:09:55  $M_L$  1.1



# 미보고 지진 탐색

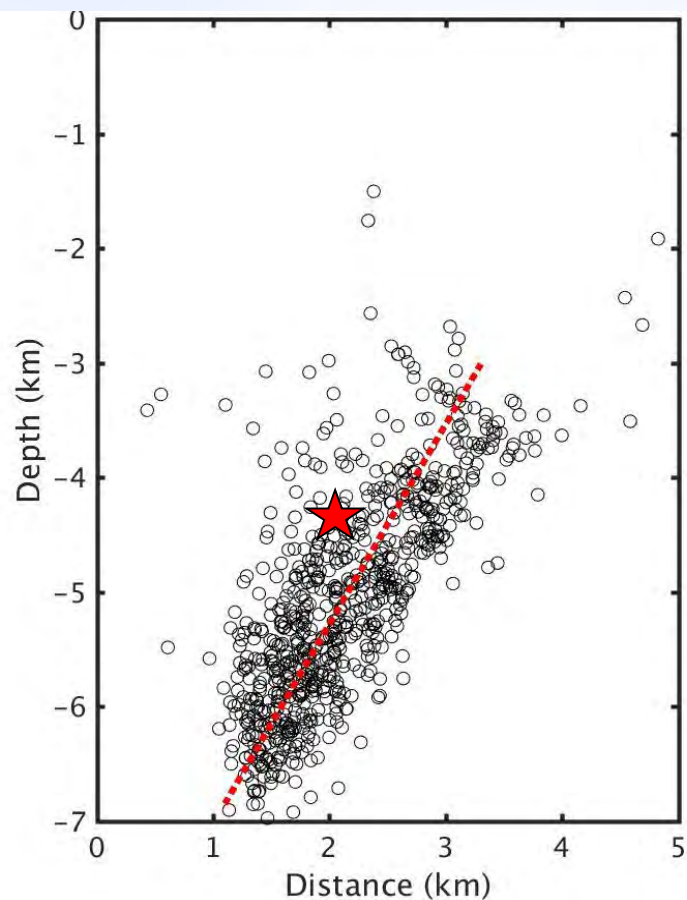
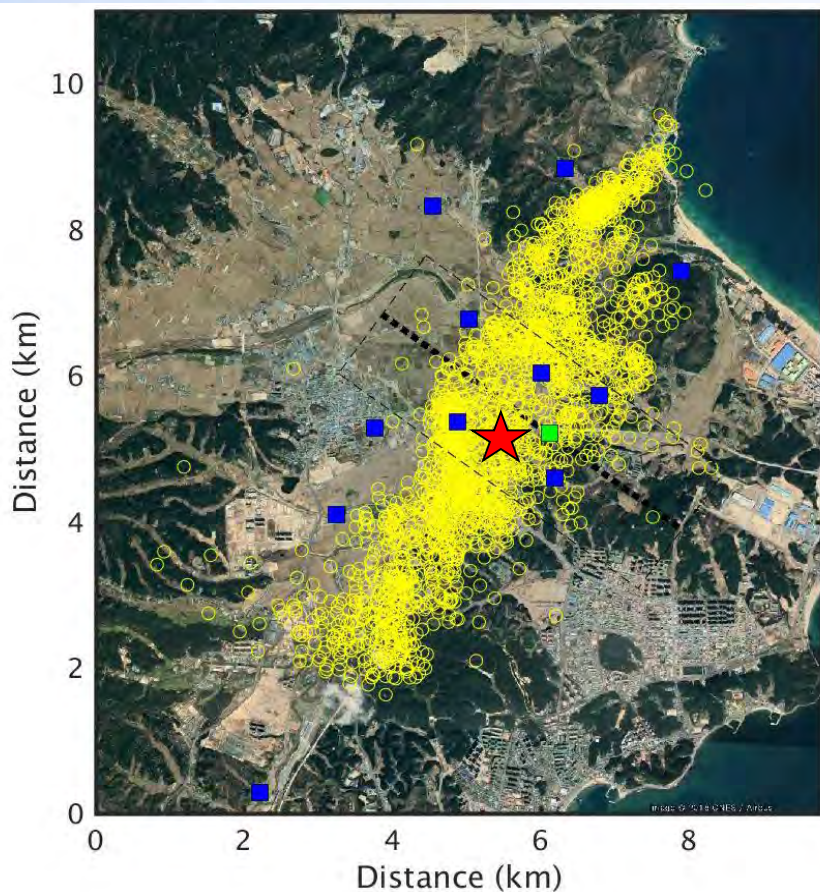
## ❖ 기상청 지진관측소 (PHA2)

- 지열발전소 북쪽 약 10 Km
- 2012년 장비 업그레이드
- 2012년 1월부터 2017년 11월까지 미보고 지진 탐색 (지진파형의 유사성 활용)

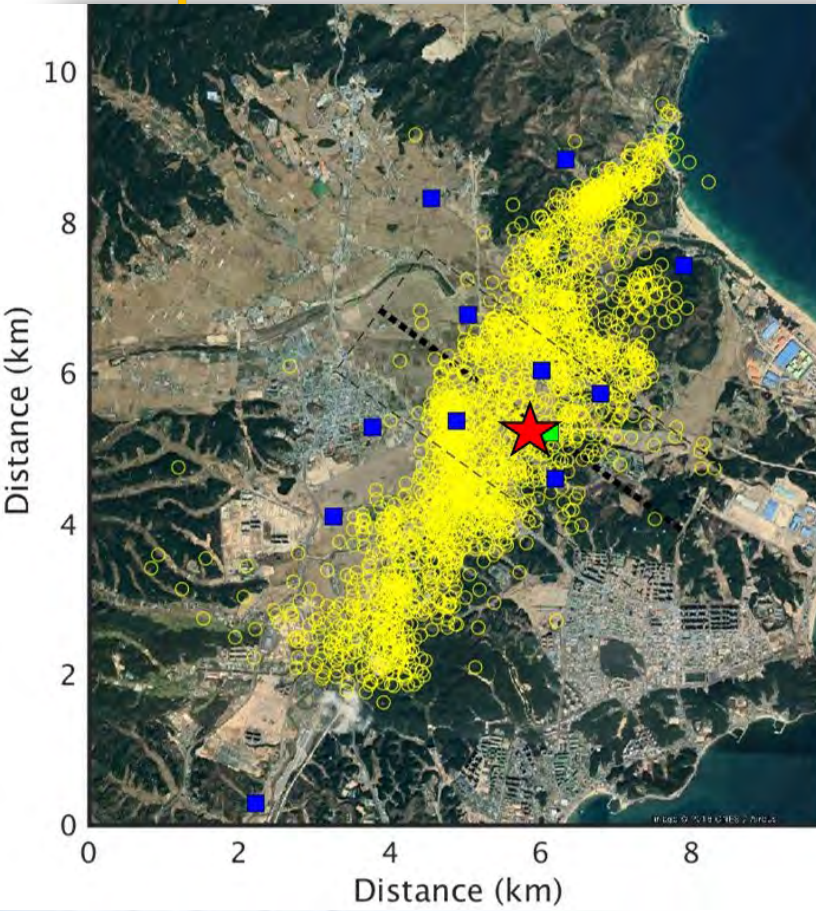


# 포항지진 발생원인?

- ❖ 포항지진 발생 이전 지진발생 현황
- ❖ 지열발전소 물 주입과 미소지진 간의 시간적 상관성
  - 물 주입 자료: 산업통상자원부 제공
  - 미소지진 자료: 미소지진목록 (본 연구, **matched-filter**)
- ❖ 주입정/생산정의 위치/깊이와 전진/본진의 발생 위치 및 깊이
- ❖ 여진 분포로부터 확인한 지하 단층의 위치와 생산정/주입정의 위치/깊이



# 포항 지열발전소와 지진



Road view



Birdview



View from PH07



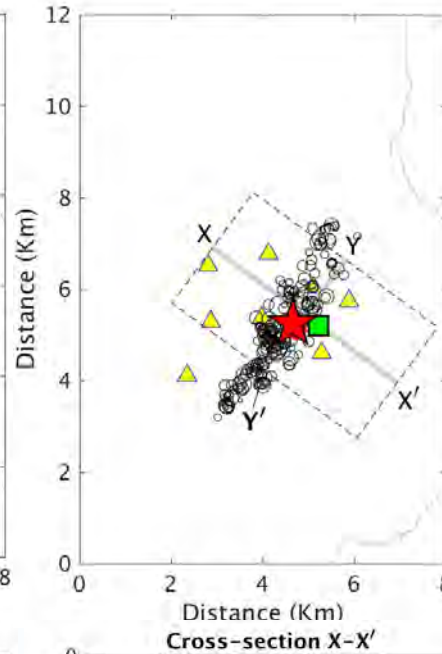
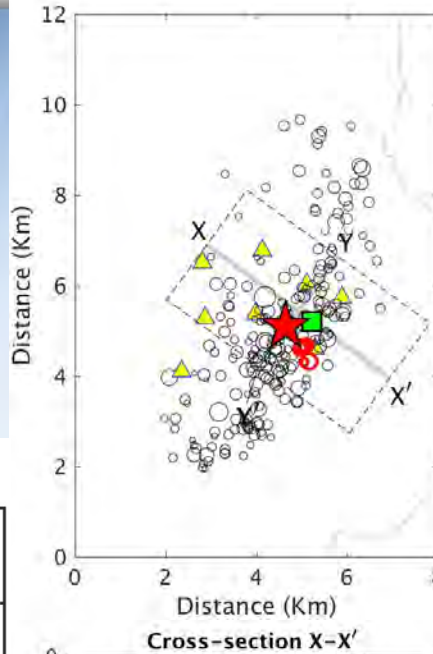
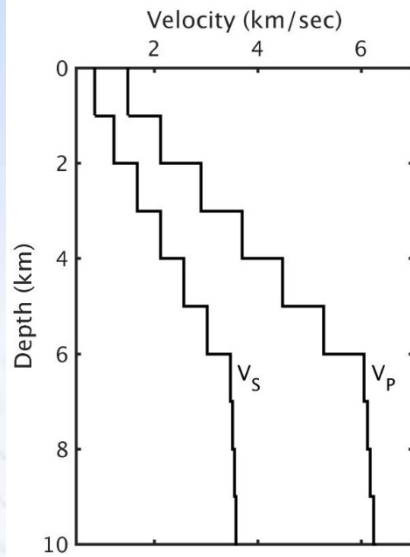
# Pohang Enhanced Geothermal System (EGS)

- ❖ 계획용량: 1.2 MW
- ❖ 시추목표 깊이: 4,500 m
- ❖ 예상온도: 180 °C
- ❖ 시추개시: 2012년 9월
- ❖ 시추완료: 2015년 11월  
(4,382 m)
- ❖ 수리자극: 4회, 2016년 1월부터
- ❖ 총 유체 주입량: 12,798 m<sup>3</sup>
- ❖ 순 유체 주입량: 5,841 m<sup>3</sup>

# Seismicity in the first 3 hours

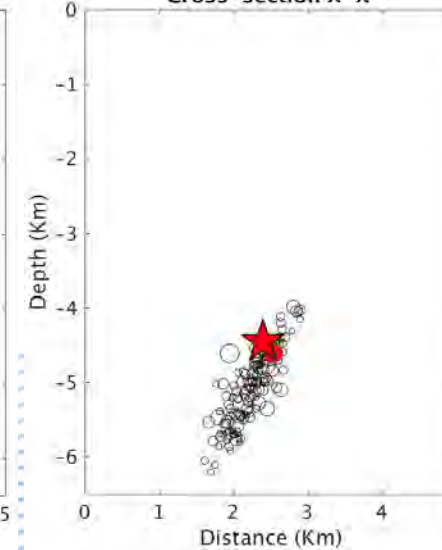
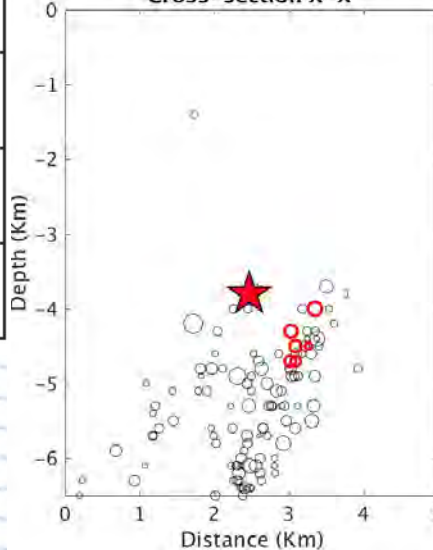
**Initial  
locations  
by Hypoellipse**

**Short period  
velocity sensors**



**Relocations  
by HypoDD**

- ❖ 8 stations
- ❖ 218 events
- ❖ 69,304 P dtimes
- ❖ 56,262 S dtimes



**Mean uncertainty from HypoDD:  
31m (EW), 33m (NS), 25m (Depth), 0.5 sec**