Current status and issues of research on induced earthquakes in Sichuan Basin

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- Promotion of integrated observation and research

Major references

SCIENCE CHINA
Earth Sciences

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•REVIEW•

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Growing seismicity in the Sichuan Basin and its association with industrial activities

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Abstract In the Sichuan Basin, seismic activity has been low historically, but in the past few decades, a series of moderate to strong earthquakes have occurred. Especially since 2015, earthquake activity has seen an unprecedented continuous growth trend, and the magnitude of events is increasing. Following the *M*5.7 Xingwen earthquake on 18 Dec. 2018, which was suggested to be induced by shale gas hydraulic fracturing, a swarm of earthquakes with a maximum magnitude up to *M*6.0 struck Changning and the surrounding counties. Questions arose about the possible involvement of industrial actions in these destructive events. In fact, underground fluid injection in salt mine fields has been occurring in the Sichuan Basin for more than 70 years. Disposal of wastewater in natural gas fields has also continued for about 40 years. Since 2008, injection for shale gas development in the southern Sichuan Basin has increased rapidly. The possible link between the increasing seismicity and increasing injection activity is an important issue. Although surrounded by seismically active zones to the southwest and northwest, the Sichuan Basin is a rather stable region with a wide range of geological settings. First, we present a brief review of earthquakes of magnitude 5 or higher since 1600 to obtain the long-term event rate and explore the possible link between the rapidly increasing trend of seismic activity and industrial injection activities in recent decades. Second, based on a review of previous research results, combined with the latest data, we describe a comprehensive analysis of the characteristics and occurrence conditions of natural and injection-induced major seismic clusters in the Sichuan Basin since 1700. Finally, we list some conclusions and insights, which provide a better understanding of why damaging events occur so that they can either be avoided or mitigated, point out scientific questions that need urgent research, and propose a general framework based on geomechanics for assessment and management of earthquake-related risks.

Keywords Induced seismicity, Fluid injection, Sichuan Basin, Shale gas, Wastewater disposal, Salt mine

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评 述

四川盆地南部持续增长的地震活动及其与工业注水活动的关联

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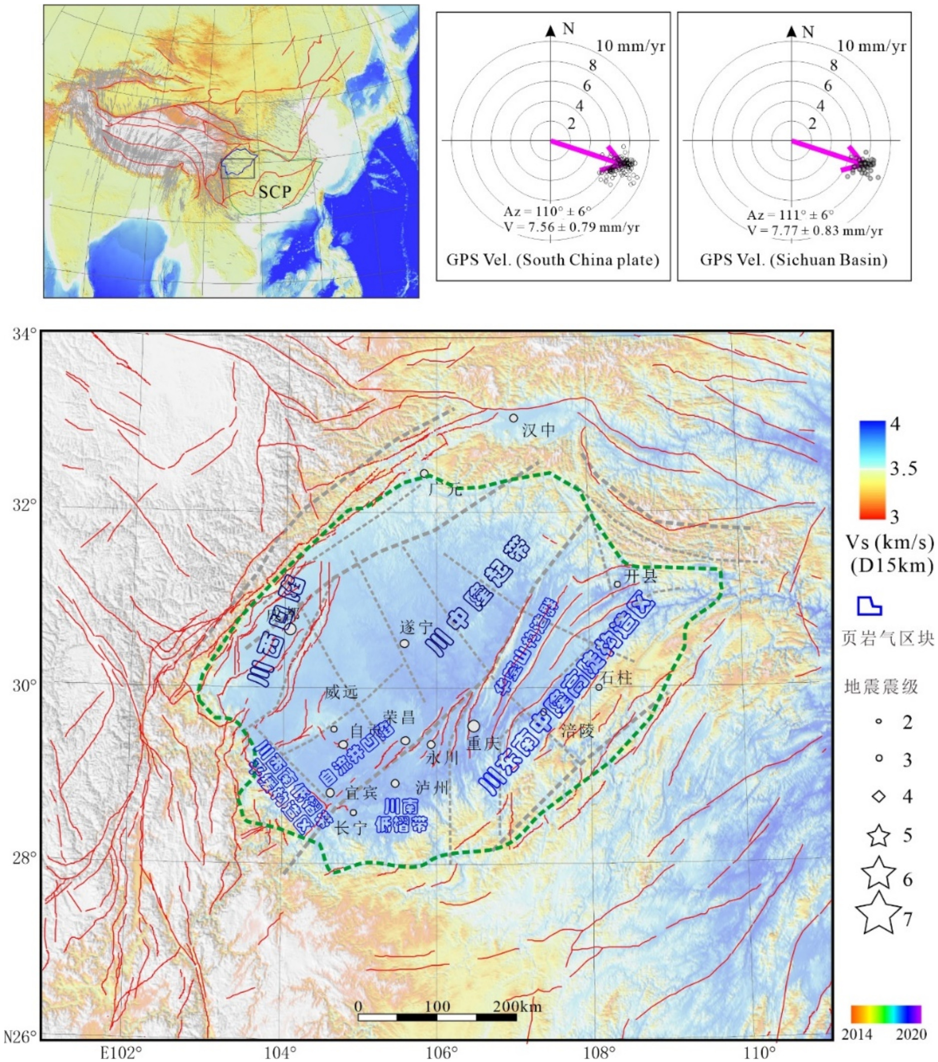
摘要 处于稳定扬子地块西北边缘的四川盆地, 其西北和西南边界为强烈地震活动带, 东北和东南部边界为变形强烈的褶皱带, 但盆地内部具有很小的应变速度, 历史上地震活动本来不高, 但在过去几十年以来, 发生了一系列中强地震. 尤其2015年以来, 地震活动出现前所未有的持续增长趋势, 且震级越来越大. 最近, 继2018年12月18日兴文5.7级地震后, 主震震级达6.0级的震群活动(长宁双河震群)袭击了长宁双河镇及周边地区. 初步研究表明, 兴文地震可能是迄今为止页岩气水力压裂诱发的最大地震. 而长宁双河6级地震有可能与附近深井采盐注水有关. 实际上, 除近年方兴未艾的页岩气开发以外, 过去40年, 在四川盆地西南部天然气田和井盐矿区存在持续的以废水回注和井盐开采为目的的注水活动, 并诱发了不同规模的地震活动. 各个注水现场具有不同的构造环境和注水规模, 为研究与注水诱发地震相关的科学问题提供了很好条件. 在这里, 文章对四川盆地内部尤其南部地区的历史地震及最近几十年来观测到的主要地震活动进行总结分析. 首先, 对1600年以来的5级以上地震进行了归纳, 得到背景地震活动频度及最近几十年的异常增加的地震活动趋势与工业注水活动的可能关联. 其次, 针对1970年以来主要地震或地震序列, 在综述以往研究结果的基础上, 结合最新数据, 综合分析了盆地内部天然成因和与注水有关的地震活动的特征和破坏性诱发地震的发生条件, 并提出一个基于地质力学分析的诱发地震风险评估管控宏观框架. 为开发规避或减轻诱发地震风险相关技术并最终使相关产业能够更加安全和有效的开展下去提供一些有关的断层活化和诱发地震研究领域的一些急需解决的科学问题.

Tectonic background of Sichuan Basin



Northwestern part of the stable South China Plate (SCP)

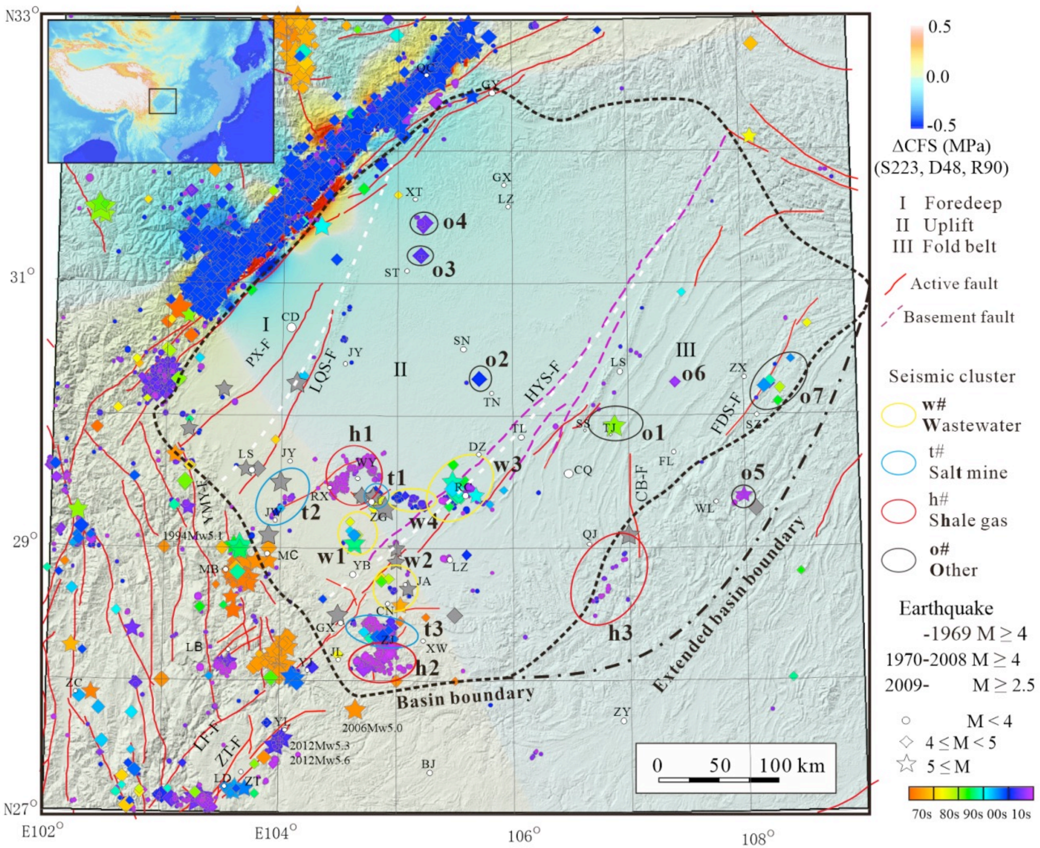
GPS data shows that the entire SCP has the characteristics of coordinated motion as a whole

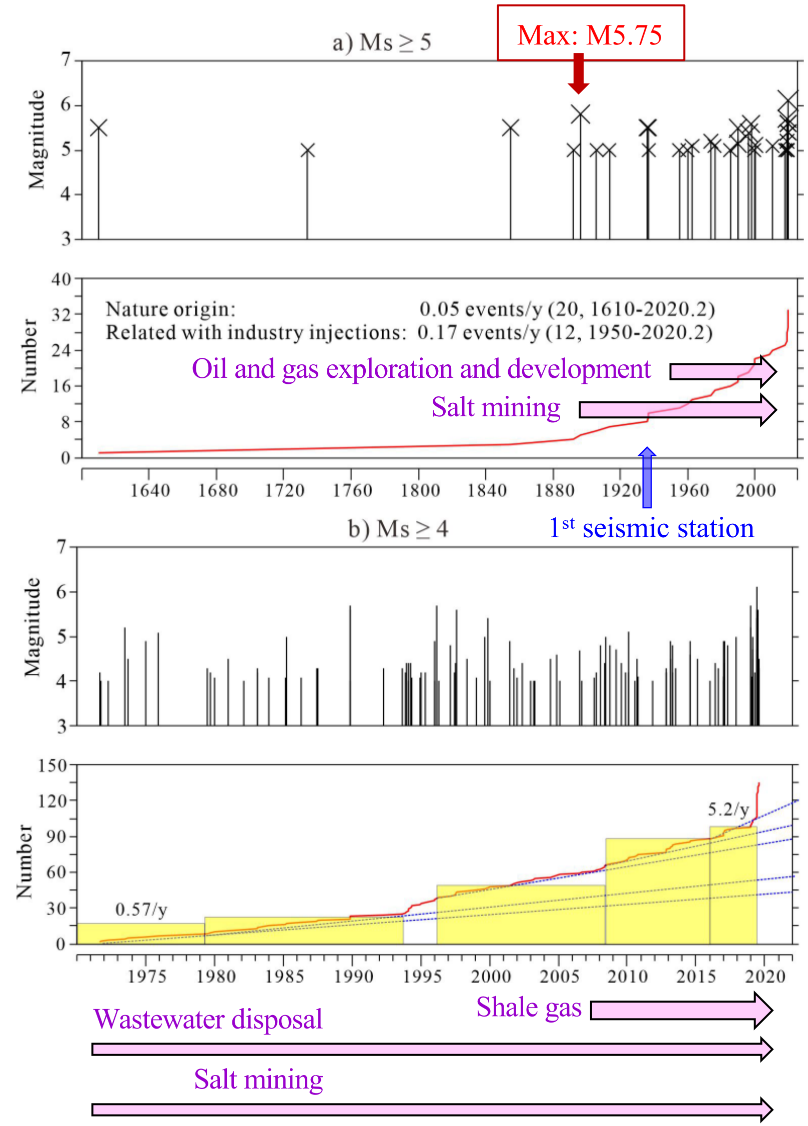
Strain rate is very low

Seismically quiet?
Rare but not zero!

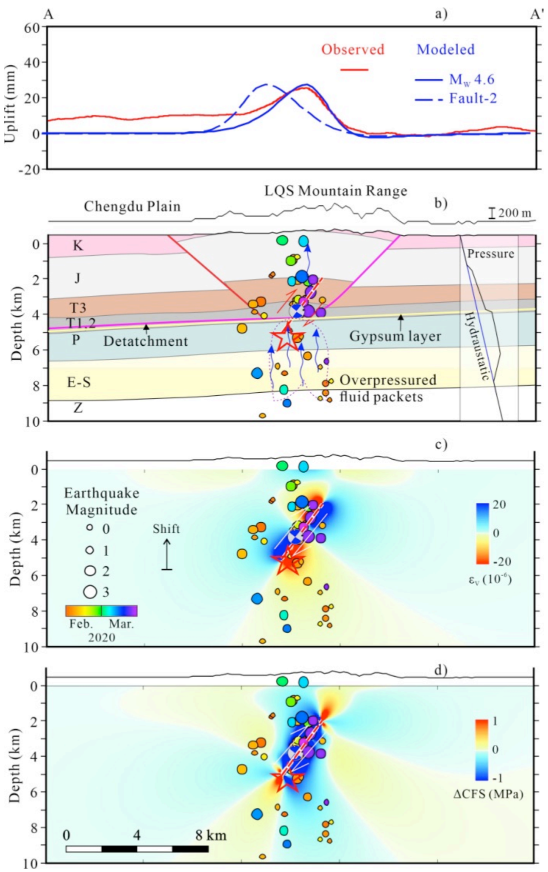
GPS data from :
Zheng et al.,2017

Major earthquakes within Sichuan Basin



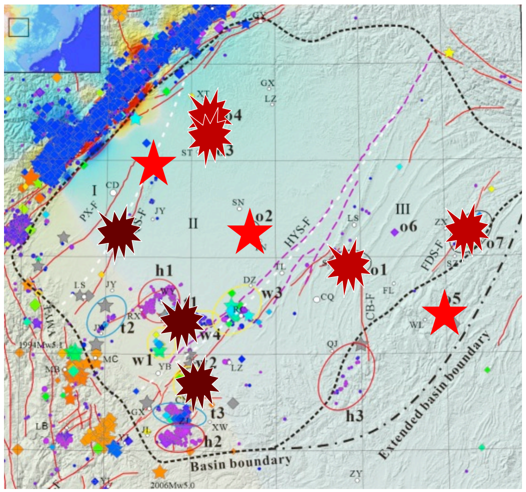


Insights from nature-origin EQs

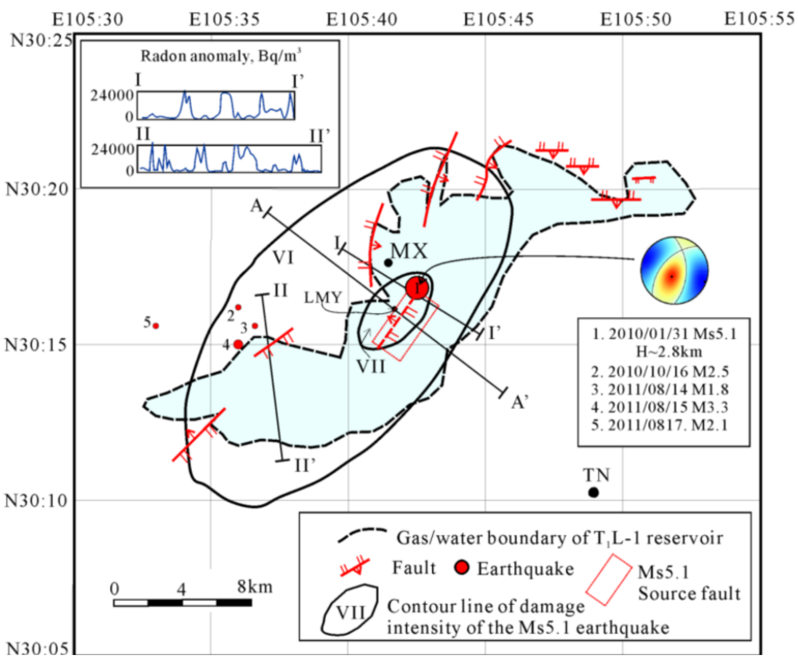


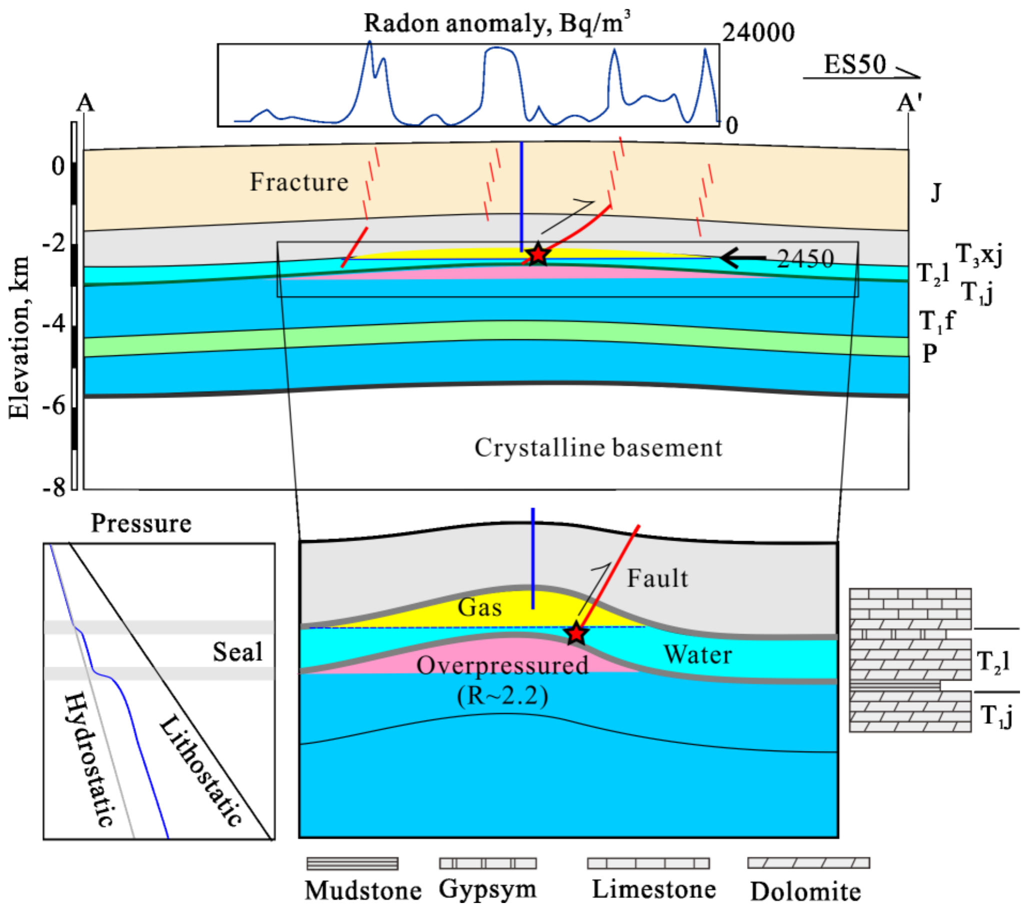
2020/2/1 Qingbaijiang Mw4.6
Lei et al, ERC, accepted

- Isolate earthquakes
  - ~M5
- Swarms
  - A few M4+ events with some fore- and/or after-shocks
- Focal depth: a few kms to more than 10 km
- Distribution：spots rather belt
- Driven by deep overpressured fluid?



2010/1/31 Tongnan Ms5.1





Isolated event

Possibly driven by high pressure gas flow

from Jialingjiang formation to Leikoupo formation

Lei et al.,2017

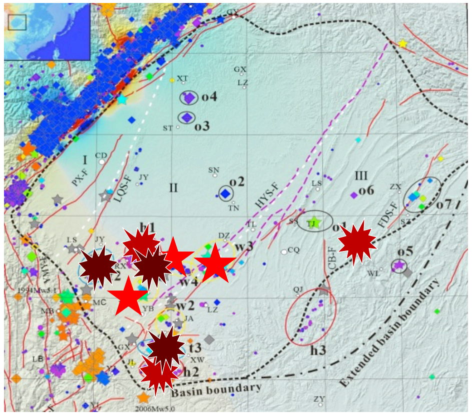
Studies on induced seismicity in SCB

- Kongtan NG field
  - M5.4, 1980-2008
    Du et al., 2002
  - Seismic activity basically disappeared
- Rongchang NG field
  - M5.2, 1980-2013
  - 1980s – 2006 : seismicity correlated with injections
    Lei et al., 2008 ; Ding et al., 2004
  - Post-injection seismicity with M5
    Wang et al., 2020
  - Shale HF started in 2019
- Huangjiachang NG field
  - M4.4, 2009-2010
    Lei et al., 2013 ; Zhang et al., 2012
  - Decay quickly after shut-down

- Ziliujing salt mine
  - M4.6 –5.0, 1947-,
    Zhang et al., 1993
- Luocheng-Changshan
  - M4.2, 1970-, Lv et al., 2009
- Changning
  - M4.8, -1971-, Yuan et al., 2008
  - 1990-2015, Sun et al, 2017
  - 2019 M6 swarm
    Chen et al., 2020
    Jiang et al., 2020
    Lei et al., 2019;
    Li et al., 2020; ->RupDir
    Liu et al., 2020;
    Long et al., 2020;->
    Wang et al., 2020;->InSAR
    Yi et al., 2019 ;
    Zuo et al., 2020;

    ……

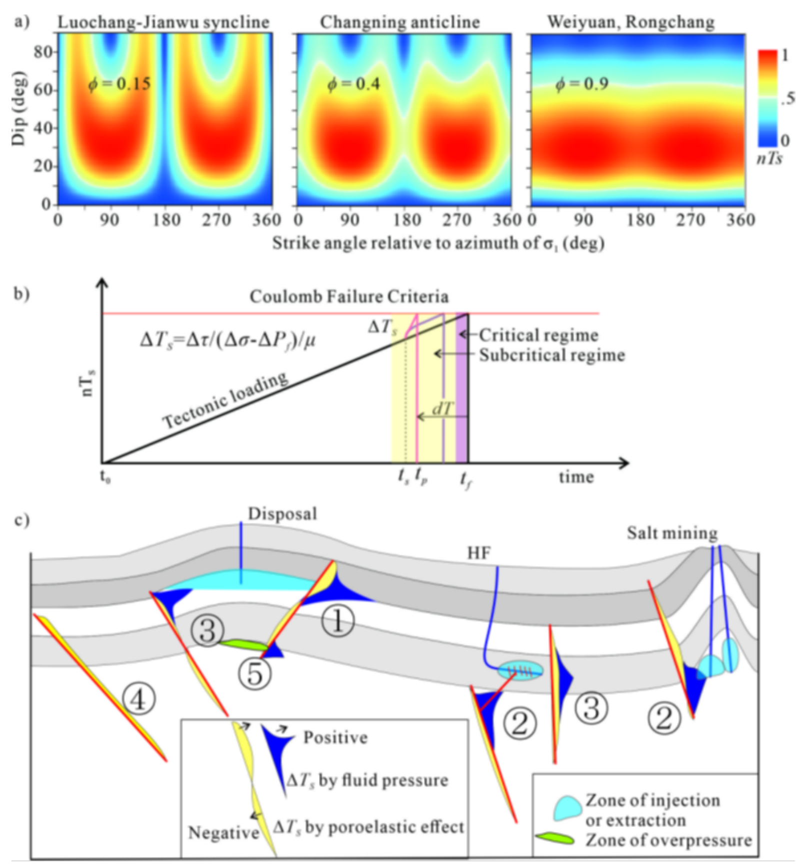
- Wei-Rong shale gas
  - 2008-, M5.4
    Chen, et al., 2018
    Lei et al., 2020
    Sheng et al., 2020
- Changning
  - M5.7, 10 M4+, 4 M5+
    He et al., 2019
    Jia et al., 2020
    Lei et al., 2017; 2019
    Meng et al., 2019
    Tan et al., 2020



Insights from induced seismicity

- Both long-term (<~10 MPa) and short-term (>~60 MPa) injections induced earthquakes up to M5.5~6.1
- Caused by reaction of pre-existing faults
- Under different stress regime
- Fluid pressure plays dominated role
- Show very low aftershock productivity
- Kept active during injection and after shout-down of long injection
- Individual events show no difference with natural earthquakes
- Shows site dependence governing by
  - Density, size, orientation, maturity of fault
  - Stress regime
  - Injection parameters

Equivalent to natural earthquakes, but all shows shallow CMT depth

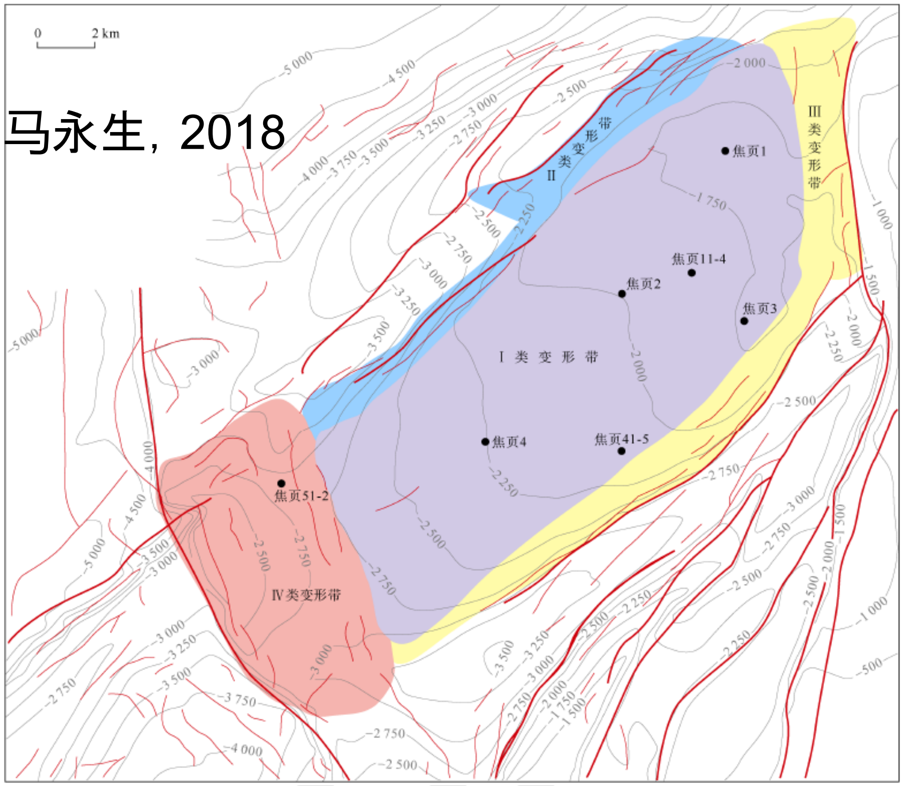


Key issues remaining poorly understood

- Link with injection operation is not very clear due to the lack of detailed injection data.
- Precise seismogenic structures
- Rupture process of large events
- Conditions of large events
- Why large events shows very low aftershock productivity?
- Predictability?
- Can large event be effectively avoided

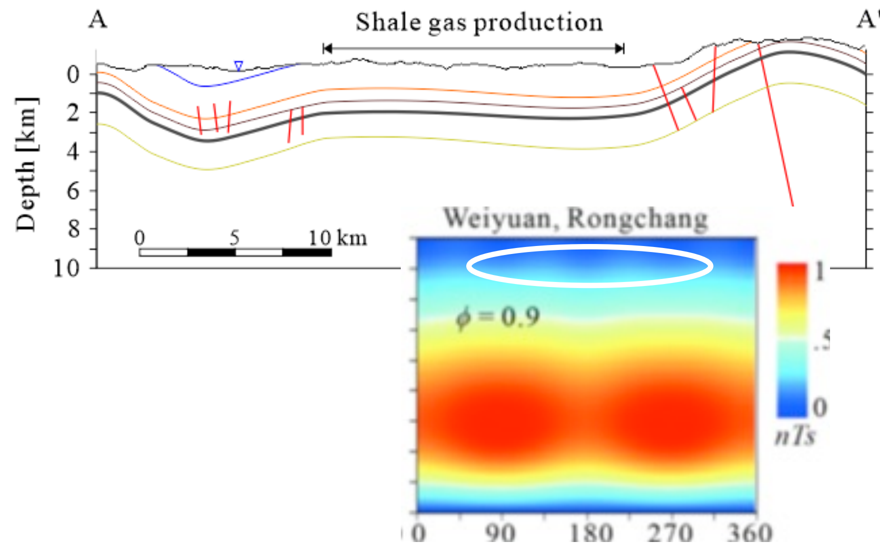
- Understandings can be greatly improved with detailed water injection data and 3D seismic data

Jiaoshiba



500 构造等高线/m　大断层　次级断层

Ⅰ类变形带：地层产状平缓，构造简单，孔隙度大于 4.6%，含气量大于 6.0 m^3/t，单井平均无阻流量大于 50×10^4 m^3/d；
Ⅱ类变形带：构造变形较复杂，断裂封堵性较好，孔隙度大于 4.0%，含气量大于 6.0 m^3/t，单井平均无阻流量大于 40×10^4 m^3/d；
Ⅲ类变形带：构造变形较复杂，断裂封堵性较差，平均孔隙度 3.8%，平均含气量 5.5 m^3/t，单井平均无阻流量小于 20×10^4 m^3/d；
Ⅳ类变形带：构造复杂，乌江断裂封堵性差，平均孔隙度 2.9%，平均含气量 5.0 m^3/t，单井平均无阻流量小于 10×10^4 m^3/d



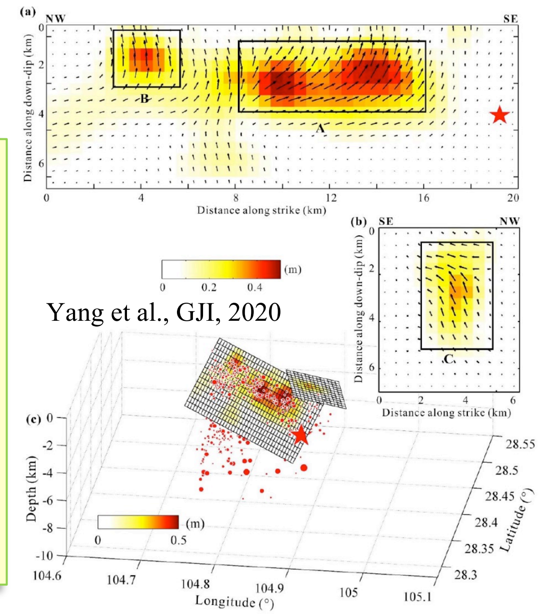
- Flat sedimental layer without significant faults
- Surrounded by high-angle reverse faults
- These faults are unfavorable

Changning earthquake

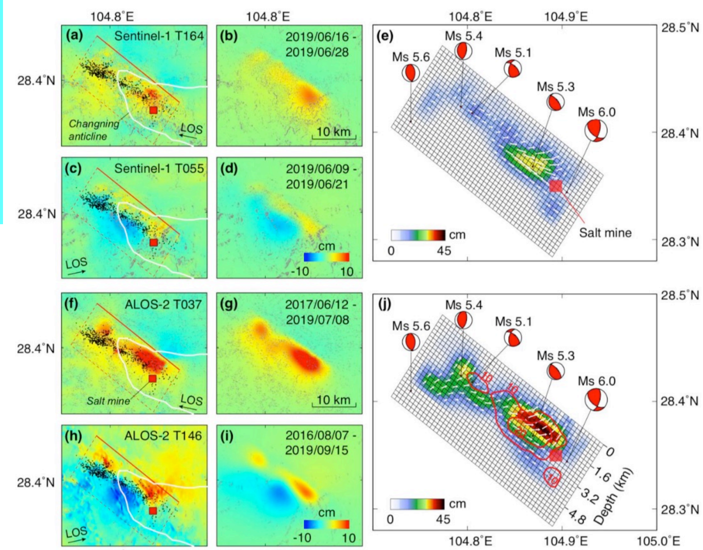
- Rupture directivity: northwestward (Li et al., 2020)
- Strike: longer, 14~17km
- Dip: shallow & narrow, ~4 km
- Not mapped
- Complex geometry
  - Multi segments of different geometry
- East segment: dip=30
- West segment: dip=30-90, Controversial

InSAR
1-segment
D31°（Wanget al)
D27° (Yang et al.)
2-segments
D31, D90 (Sun et al.)
CMT
122/51/28 (Lei et al.)
131/51/36 (Yi et al.)
Doublet
170/35/111+116/72/5 (Liu et al.)

Source faults can not be fingered out by hypocenter distribution of aftershocks

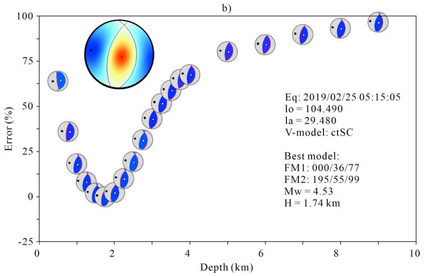


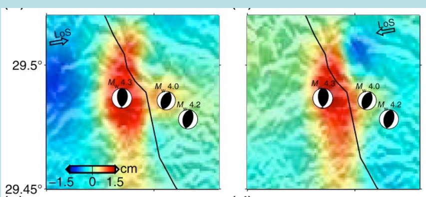
Yang et al., GJI, 2020



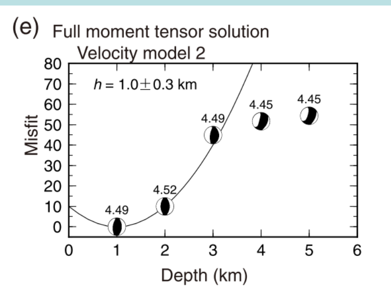
Wang et al., GRL, 2020

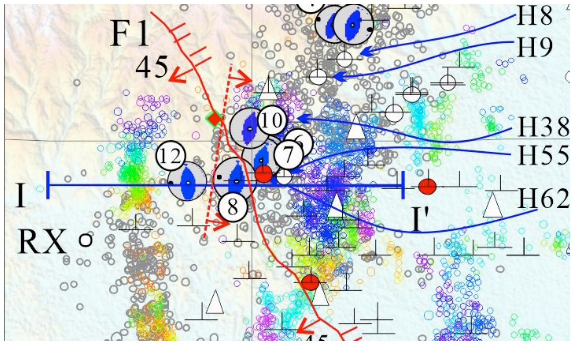
Weiyuan earthquakes

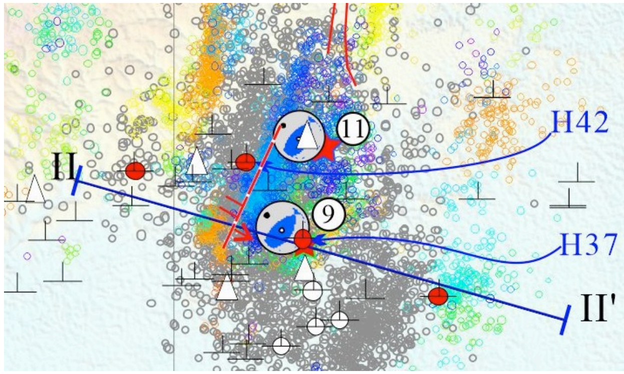


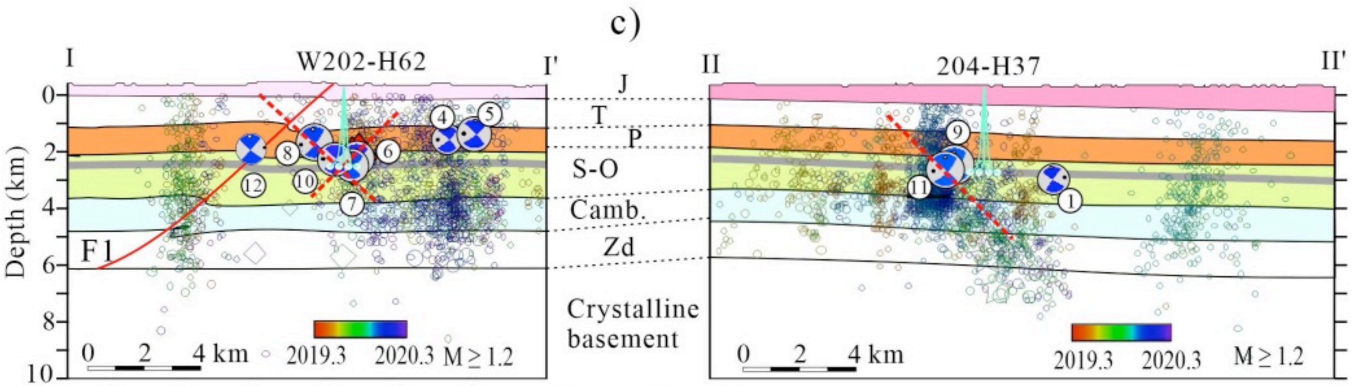


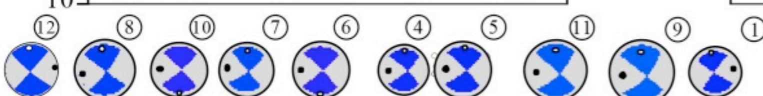
Yang et al., 2020





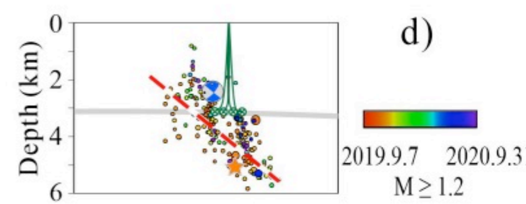






①2014/07 ②2016/01 ③2016/07 ④2018/07
⑤2018/07 ⑥2019/02 ⑦2019/02 ⑧2019/02
⑨2019/09 ⑩2019/09 ⑪2019/12 ⑫2020/02

Lei et al., 2020



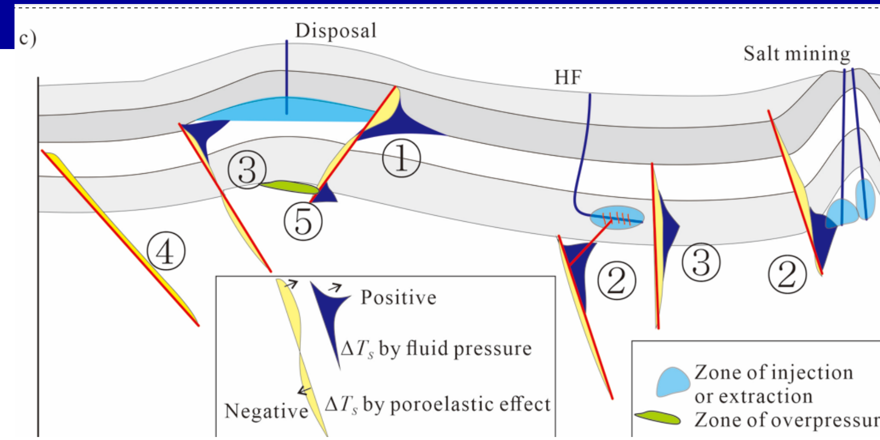
- Controversial results among different studies

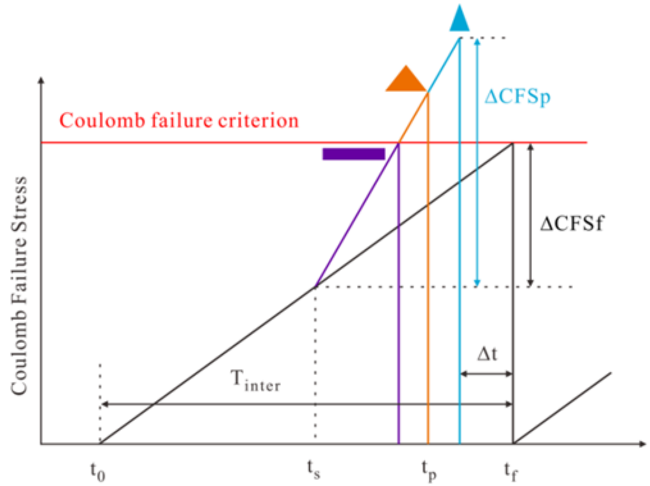
201/68/75
Sheng et al., 2020

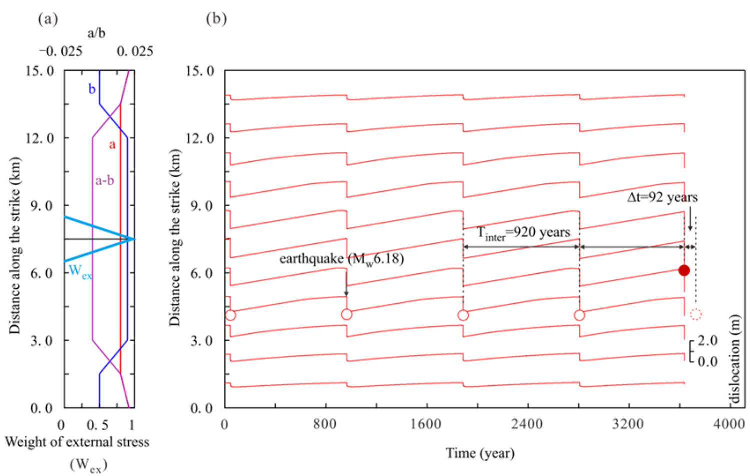
Key problems in futural studies

- In-depth analysis of past cases to deepen and refine our understandings
  - Seismogenic structures
  - Rupture process of large event
  - Condition of damaging events
  - Reassessment
  - Risk prediction technology
    - Sign of fault reactivation?
    - Statistics of induced seismicity
- Promotion of integrated obs. & research
    - Monitoring, detecting sign of fault reactivation
    - Feedback to operator
- Industry-academia-government collaboration
  - Government:
    Policies and regulations
  - Industry:
    Share their data, joint-work
  - Academia :
    Provide support for effective and safe production
- Fundemental research
  - Slip behaviours and hydraulic characteristics of faults of different maturities and host rocks
  - Role of localized overpressure on fault reactivation
  - Risk reduction technology
    - Laboratory study
    - Numerical study
    - Reservoir scale experiment
- Management and control framework of risks related with fault reactivation and induced earthquakes

Stress perturbation on fault



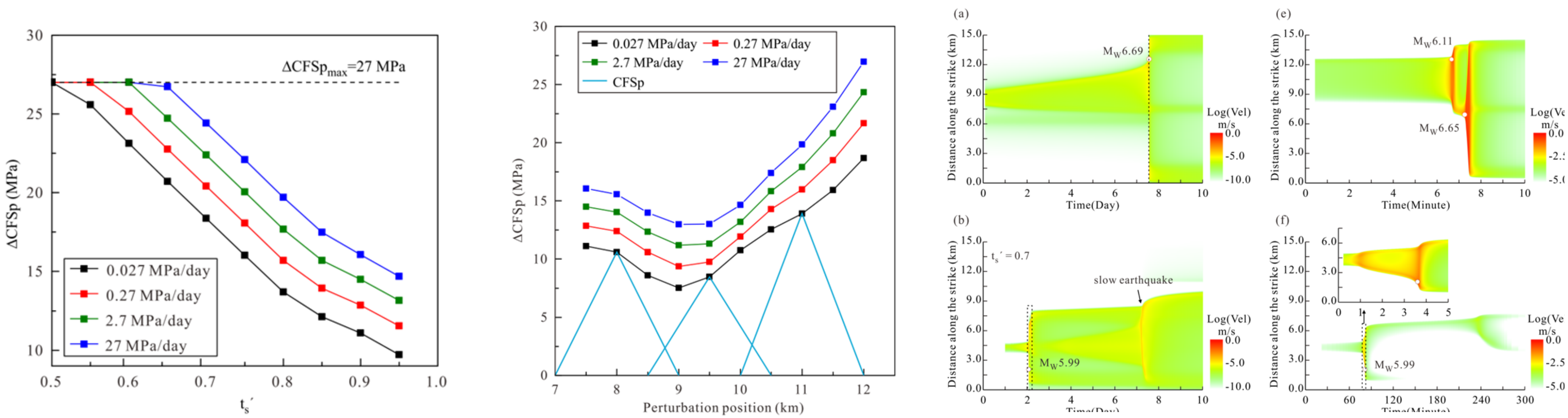




Huang et al. in preparation

- Distribution SP govern by
  - Distance to injection
  - Connectivity
  - Permeability
- Stress criticality govern by
  - Stress pattern
  - Fault orientation
- Faut reactivation govern by
  - SP, SC
  - Frictional properties
  - Healing status, roughness
  - …….

Preliminary results of an ongoing study based on rate- and state-dependent law

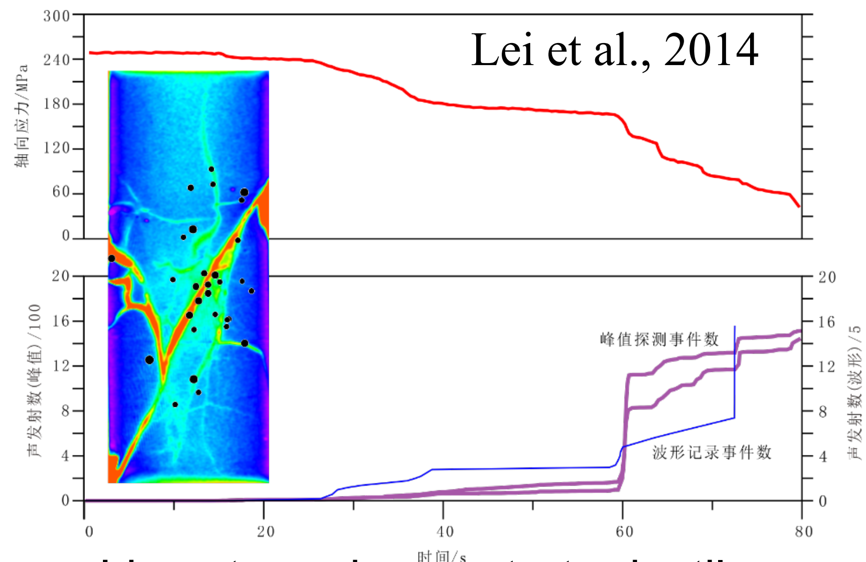


Huang et al. in preparation

- Under sufficiently large stress fluid pressure (in possible range of HF), a fault of tectonic stress far below the critical point can be reactivated
- Stress criticality of the fault, distribution (range, position, increasing rate) of fluid pressure on the fault zone play a dominant
- Slow-slip events even in velocity-weakening zone
- Needs experimental study (Laboratory and field) to verify and make it practically useful

Why large events are out runner?

- Larger event
  - Out runner, Dragon-king
  - Solitary, fewer aftershocks
- Possible factors
  - Fault is healed
  - Rough surface
  - Unsustainable driving fluid
  - Ruptured/smoothed fault demonstrated velocity-hardening behaviors



Limestone demonstrate ductile fracturing with some brittle event

Drainage conditions dominate fracture (seismic or aseismic) of porous rocks（Lei et al., 2011）

Monitoring and detecting sign of fault reactivation

- 4D velocity imaging
  - Detailed 3D <- operator has done good work
- Seismicity,
  - Integrated, all scales
- Deformation
  - Optical fiber
  - InSAR
- Field experiment

- Detecting sign of fault reactivation
  - Seismicity image
  - Statics of seismicity
  - Localized deformation