Insights on Injection-induced Seismicity Gained from Laboratory AE Study—Fracture Behavior of Sedimentary Rocks

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Abstract

Injection-induced seismicity associated with applications, in which fluids are intensively pressed into the deep formations of the Earth's crust such as Enhanced Geothermal System (EGS), fracking shale gas, geological sequence of CO\textsubscript{2}, have attracted growing attentions. Motivated by the desire to better understand the mechanism of damaging events so that they can be avoided or mitigated, we have started an integrated study on rock fracturing and fault reactivation in multiscales. In this paper, we present some preliminary results of an ongoing experimental study utilizing acoustic emission technique in laboratory scale. We systematically carried out rock fracture tests using samples of typical sedimentary rocks collected from the Sichuan Basin, China, where a number of injection-induced seismic swarms with sizable earthquakes ranging up to M4~5 have been observed in some gas/oil reservoirs. Since most injection-induced earthquakes are located in sedimentary strata of a wide range of lithology and depth, the fracturing behaviors of such rocks are thus important. Our results indicate that the Pre-Triassic rocks in the Sichuan Basin, including dolomite or dolomitic limestone and shale are strong and demonstrate brittle fracturing behaviors. Such properties are necessary conditions for maintaining high level reservoir stress and resulting seismic fracturing.

Keywords: Acoustic Emission, Rock Fracturing, Sedimentary rocks, Injection-Induced Seismicity

1. Introduction

In applications including Enhanced Geothermal System (EGS), fracking shale gas, and geological sequence of CO\textsubscript{2}, fluids of various viscosity and temperature are intensively pumped under high pressure into the deep formations of the crust. In recent years, associated with the rapid increase of such applications, injection-induced seismicity has attracted growing public and scientific attentions. Earthquakes of moderate sizes (~M5), which are damaging in areas having not experienced with large earthquakes in the history, were occasionally observed. Injection induced seismicity is not required but unavoidable in many cases (Technologies et al., 2012). The impact of induced earthquakes is a controversial issue that has caused delays and threatened cancellation of some projects, such as the recent project at Basel (Kraft et al., 2009). It is thus a scientific challenge to make clear the mechanism and geomechanical conditions of damaging events so that they can either be avoided or be mitigated.

The cases, especially recent ones, of injection-induced earthquake sequences in the southwestern Sichuan Basin, which is a relatively stable region in China showing very low level of background seismicity, provide us a chance of comprehensive studies on which. During the past three decades, a number of seismic sequences have been observed with sizable earthquakes ranging up to M4~5. Their timing, location and occurrence pattern involved in statistical models, convincingly suggest that these sequences were induced by injections of unwanted water in deep wells in depleted gas fields. All sequences were initiated in days to a few weeks after water injection under high pressure begun. Event rate fluctuates following changes of injection rate and injection frequency and tapered quickly after shut down. Detailed studies on some recent and well monitored cases demonstrate that most events, particularly larger ones, mirror the reactivation of pre-existing faults (including joints and fractures) in the sedimentary formations or faults underlying/overlying the reservoir (Lei et al., 2013b; Wang et al., 2012). As a typical example, Fig.1 shows hypocenter distribution of injection-induced earthquakes superimposed on the simplified geological cross section and stratigraphy of a gas
reservoir in Zigong city, located in southwest of the Sichuan Basin. More than 90% of hypocenters were determined within the Permian dolomitic limestone dominated strata surrounding the depleted gas reservoir. Shale and mudstone in the overlying and underlying strata act as fluid diffusion barrier and play a role in arresting fractures in the dolomitic limestone formation. At the front of hypocenter clouds, seismic activity is clearly bounded by dipping faults leading to upward and downward migrations. Two M4+ events show a revise faulting mechanism indicating reactivation of pre-existing faults of relative high dipping angle, which are known from petro-geophysical investigations. The largest event (M4.4) was probably initiated in the Pre-Cambrian dolomite formation underlying the depleted reservoir. It is known that typical mudstone, shale, and limestone pronounce ductile fracturing behaviors under high pressure. It is thus an interesting issue to make clear the mechanism of injection-induced earthquakes in the Sichuan Basin. Motivated by such purpose, we have started an integrated research including laboratory study on the fracture behaviors of typical reservoir rocks.

Here, we report some preliminary results from triaxial compression tests of rock samples collected from typical formations of gas reservoirs in the Sichuan Basin. Rock fracture tests under dry condition were performed at a confining pressure of 22.5 MPa, which corresponds to a depth of ~1 km, typical for many injection applications such as geological storage of CO₂.

![Diagram of geological cross section](image)

Fig. 1 Hypocenter distribution of injection-induced earthquakes superimposed on the simplified geological cross section and stratigraphy of the Huangjiachang gas reservoir (indicated by the cross lines in the inset map) in the southwestern Sichuan Basin, China (Modified from Lei et al., 2013b).

2. Experiments

2.1 Rock sample

In order to investigating the fracture behavior of typical reservoir rocks under triaxial compression conditions, we collected various kinds of rock blocks from a field geological survey in the Sichuan Basin. The test rocks in this study are 1) Middle Jurassic sandstone of Xiaximiao formation (J₃x); 2) Lower Triassic limestone of Feixianguan formation (T₁f); 3) Precambrian dolomite of Dengying formation (Zd); and 4) Precambrian shale of Zd. In the Sichuan Basin, typical reservoirs are found in formations of sandstone of very low permeability, limestone, and dolomite. Shale strata are one of the major cap rocks. Tab. 1 lists major mechanical and physical properties of these rocks.

The test samples were shaped into cylinders of 125 mm length and 50 mm diameter. All samples were dried under normal room conditions for more than one month and then they were compressed at a constant stress rate or at a constant stress (creep test) at a stress level of ~95% of the nominal fracture strength at room temperature (air-conditioned at ~25°C). During the deformation, the confining pressure was maintained at a constant level of 22.5 MPa (or 10 MPa in some case). Under these conditions, the rock samples are normally fractured along a compression shear fault oriented at 0~30° with respect to the axis which is the direction of the maximum compressive stress.
Once the rock is pressurized, a selected AE event can be recorded at the rate of 25 kHz and a sample length of 256 mega words (MW) capacity. Twenty-four piezoelectric transducers (PZT) of 5 mm in diameter having a resonant frequency of 2 MHz were mounted to the curvilinear surface of the test sample for AE monitoring and velocity measurement. The signal from every AE sensor is pre-amplified by 40 dB before feeding into the waveform recording system. In this study, AE signal is digitized with a sampling rate of 25 MHz and a sample length of 4096 words (~160 microseconds). Furthermore, six cross-type strain gauges were mounted to the surface of the sample for strain measurements, which are digitized with varying sampling interval between 0.001 and 1 second. Two peak detectors were used to capture the values of the maximum amplitudes, from 2 artificially selected sensors, after 20 or 40 dB pre-amplifiers. An automatic switching sub-system was used for sequentially connecting every selected sensor, in total 18, to the pulse generator of 20V pp volt output for velocity measurement.

The new waveform recording system has three working modes: single-event mode, multi-event mode, and continuous mode. In the single event mode, the digitized waveform data of a triggered AE event are directly transformed to the hard disk of the host PC. As a result the system can record at most 10 events per second until the hard disk array is full. Thus the single-event mode is applied during earlier stages of loading, in which AE rate is less than 10 events per second. For later stages, we normally switch the system to the multi-event mode, under which the system can record up to ~5000 events per second since digitized waveform data are directly stored in the onboard memory. Once the onboard memory is full (65536 events under aforementioned sampling conditions),
waveform data are automatically transformed to the host PC. We can also force the system to transfer the onboard data at any time through the interactive user interface of the waveform data acquisition software-TSpro (Fig.2).

Fig.3 shows typical loading paths used in the experiment. In this study, we focus only on results of fracture tests performed under dry condition (Fig.3 A). Results of fracture tests under wet condition and hydro-fracturing tests will be reported in later papers.

After the experiments, 3D X-ray CT scanning is carried out for all broken samples. The resolution of the CT image is 0.2 mm/pixel, sufficient for examining the mesoscale structures and fault geometry in the sample. We can relate the direction of formation and loading axis for shale and sandstone sample since we can easily identify the bedding planes of these rocks.

![Diagram](image)

Fig.3 Schematic diagram showing loading paths and possible post failure processes, stick-slip or stable sliding. In case A), the test rock is faulted due to increasing axial stress while case B) is designed for hydro-fracturing test.

3. **Experimental results**

Figs. 4-7 show key results of rock fracture test of the four rocks listed in Tab. 1. Follows are a brief summary. For convenience, we simply term the AE events before and after the dynamic fracturing as foreshock and aftershock, respectively.

The **sandstone** sample shows very large volumetric strain indicating significant compressibility. An accelerated increase of AE activity is observed immediate before the peak stress and a large number of aftershocks are observed. Foreshocks are randomly located in the central part of the sample while aftershocks concentrated along the final fault plane. X-Ray CT image shows that the finally created fault is complicated by bends and rough surface. The post slip data show a frictional coefficient of ~1.1, which is significantly higher than the normal range (0.6–0.8) of well-developed faults in the crust (Fig.4).

The **limestone** sample demonstrates ductile fracturing behavior in total. The axial stress dropped slowly from the peak value of 249 MPa to ~50 MPa. However, the fracturing process also contains some sub events showing rapid stress drop and thus could be seismic. Stylolite, which is the weakest structure in the limestone formation, has a dominant role on the fracturing process leading to very complicated fault geometry which can be identified from the X-ray CT image. No foreshocks were observed. During the fracturing stage, a few hundreds of AE events were recorded by the waveform recording system, among which a few tens event could be precisely located. Most events are distributed on the fault plane, but some events are clearly correlated with the Stylolite structures within the sample (Fig.5).

The **dolomite (dolomitic limestone)** sample demonstrates quit different fracturing behaviors as compared with the limestone sample. The axial stress dropped quickly (within a few seconds) from the peak value of 321 MPa to 240 MPa, and thus demonstrating more brittle fracturing behavior. No significant foreshocks occurred before the peak stress. About 2000 AE events were recorded in the short time period (~3s) after the peak stress and before the rapid stress drop begun. More than 1000 events were observed during the rapid stress dropping period. The 3D X-ray CT images of the broken sample indicate a very complicated fracture geometry characterized by bends and complex branches (Fig.6).

The **shale** sample contains strong bedding structures which are clearly reconstructed in the X-ray CT scan images (Fig.7). The bedding plane has an angle of ~25 degree with respect to the axis of the sample and thus is optimally oriented for fracturing. The finally created fracture is clearly governed by one of the bedding structures. The fracturing process is very brittle, and the axial stress dropped
very quickly from the peak (239 MPa) to ~100 MPa. No significant foreshocks occurred before the peak stress. More than 1000 aftershocks occurred immediately following the stress drop (Fig.7-P1). The fault surface is quite simple as compared with that of all other samples. Since the fault encountered the hard end pieces at both sides, additional AE events associated with over damaging were observed (Fig.7-P2).

![Graph](image1)

**Fig.4** Basic results of triaxial compression test of sandstone sample (J2x). Axial stress, axial displacement, strains, AE number counted by waveform recording system, shear stress, and frictional coefficient acted on the final fracture plane during the periods of fault formation and post rupture are plotted against time. A comparison between X-ray CT scan image of the fractured sample and AE hypocenters during different stages (F, P) are also plotted.

![Graph](image2)

**Fig.5** Basic results of triaxial compression test of limestone show axial stress, axial displacement, strains, and AE numbers against time and a comparison between AE hypocenters and X-ray CT scan image of the fractured sample.
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Fig. 6 Basic results of triaxial compression test of dolomite sample show axial stress, strains, and AE numbers against time and a comparison between AE hypocenters and X-ray CT scan image of the fractured sample.

Fig. 7 Basic results of triaxial compression test of shale sample show axial stress, axial displacement, strains, and AE numbers against time and a comparison between AE hypocenters and X-ray CT scan image of the fractured sample.
4. Discussion and conclusions

Our results indicate that the Pre-Cambrian formations in the Sichuan Basin, including dolomite or dolomitic limestone, and shale show brittle fracturing behaviors, characterized by no significant foreshocks, rapid dynamic fracturing with large stress drop, and a large number of aftershocks. The well cemented sandstone, having a porosity of ~6% and an extremely low permeability (less than 0.1 mD), also shows brittle fracturing behaviors. Unlike dolomite and brittle shale, sandstone shows increasing foreshock activity preceding the final failure.

The finally created faults in dolomite, limestone, and sandstone samples demonstrate complicated geometry, showing bends, irregular and rough fault surface, and branches. Fault in the shale sample (notes the bedding plane is optimally oriented for fracture) shows relatively simple fault plane. It is worthy to note that sample of badly oriented bedding planes normally demonstrate very irregular shear fault patterns (Lei et al., 2013a). New fault in brittle rocks shows relatively high frictional coefficient (1.0–1.2), expected to decrease to the typical range (0.6–0.8) after certain amount of slip and worth further study.

Our experimental results are helpful for understanding the question has raised in the introduction section—why injection-induced seismicity is so significant in the Sichuan Basin. Major Pre-Triassic sedimentary rocks, including dolomite, shale, and dolomitic limestone are strong and demonstrating brittle fracturing behaviors. Such properties are necessary conditions for maintaining high level reservoir stress and leading to seismic fracturing. Insights gained from this study may shed some lights to the general earthquake seismology and provide a better understanding of why damaging injection-induced earthquakes occur so that they can either be avoided or be mitigated. In general, critically or sub-critically stressed fault of a dimension of a few kms is a necessary condition for resulting M~5 class earthquakes. On the same time, AE, or in other words, micro-seismicity monitoring is also useful in risk assessment and injection management and should be fully utilized in injection applications.

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References


