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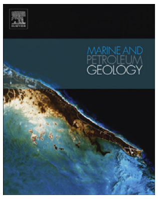

Review article

Induced seismicity and hydraulic fracturing for the recovery of hydrocarbons

Richard Davies[a,*], Gillian Foulger[a], Annette Bindley[a,1], Peter Styles[b]

[a] Durham Energy Institute, Department of Earth Sciences, Durham University, Science Labs, Durham DH1 3LE, UK
[b] School of Physical and Geographical Sciences, Keele University, Keele, Staffordshire ST5 5BG, UK

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ABSTRACT

We compile published examples of induced earthquakes that have occurred since 1929 that have magnitudes equal to or greater than 1.0. Of the 198 possible examples, magnitudes range up to 7.9. The potential causes and magnitudes are (a) mining (M 1.6–5.6); (b) oil and gas field depletion (M 1.0–7.3); (c) water injection for secondary oil recovery (M 1.9–5.1); (d) reservoir impoundment (M 2.0–7.9); (e) waste disposal (M 2.0–5.3); (f) academic research boreholes investigating induced seismicity and stress (M 2.8–3.1); (g) solution mining (M 1.0–5.2); (h) geothermal operations (M 1.0–4.6) and (i) hydraulic fracturing for recovery of gas and oil from low-permeability sedimentary rocks (M 1.0–3.8).

Reactivation of faults and resultant seismicity occurs due to a reduction in effective stress on fault planes. Hydraulic fracturing operations can trigger seismicity because it can cause an increase in the fluid pressure in a fault zone. Based upon the research compiled here we propose that this could occur by three mechanisms. Firstly, fracturing fluid or displaced pore fluid could enter the fault. Secondly, there may be direct connection with the hydraulic fractures and a fluid pressure pulse could be transmitted to the fault. Lastly, due to poroelastic properties of rock, deformation or 'inflation' due to hydraulic fracturing could increase fluid pressure in the fault or in fractures connected to the fault. The following pathways for fluid or a fluid pressure pulse are proposed: (a) directly from the wellbore; (b) through new, stimulated hydraulic fractures; (c) through pre-existing fractures and minor faults; or (d) through the pore network of permeable beds or along bedding planes. The reactivated fault could be intersected by the wellbore or it could be 10s to 100s of metres from it.

We propose these mechanisms have been responsible for the three known examples of felt seismicity that are probably induced by hydraulic fracturing. These are in the USA, Canada and the UK. The largest such earthquake was M 3.8 and was in the Horn River Basin, Canada. To date, hydraulic fracturing has been a relatively benign mechanism compared to other anthropogenic triggers, probably because of the low volumes of fluid and short pumping times used in hydraulic fracturing operations. These data and analysis should help provide useful context and inform the current debate surrounding hydraulic fracturing technology.

1. Introduction

It has been known since the 1960s that earthquakes can be induced by fluid injection. At that time, military waste fluid was injected into a 3671-m-deep borehole at the Rocky Mountain Arsenal, Colorado (e.g., Hsieh and Bredehoeft, 1981). This induced the so-called 'Denver earthquakes'. They ranged up to M 5.3, caused extensive damage in nearby towns, and as a result, use of the well was discontinued in 1966. Despite the importance of induced seismicity, only a few holistic reviews have been published (e.g., Nicholson, 1992; Gupta, 2002; Li et al., 2007). Compilations often focus on selected mechanisms although there are notable exceptions (National Academy of Sciences, 2012).

Recently, the attention of regulators, agencies and the general public has been drawn to induced seismicity linked to the hydraulic fracturing of low-permeability sedimentary rocks such as 'tight' sandstones and shale, for oil and gas exploration and production. Hydraulic fractures are stimulated to increase the surface area of

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[*] Corresponding author. Tel.: +44 7770 704198.
E-mail address: richard.davies@dur.ac.uk (R. Davies).
[1] Present address: Working Smart Ltd, Lynton House, Station Approach, Woking GU22 7PY, UK.

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rock which is connected to the wellbore. This is achieved by pumping water, proppant and chemicals during multiple fracture stages, a process known as ‘fracking’ (e.g., King, 2010). After pumping ceases the injected fluid is allowed to flowback to the surface and can be disposed of by reinjection or processing. Although hydraulic fracturing has been carried out since the 1940s, the combination of multiple stages of fracturing in horizontal wells in shale and tight sandstones and the widespread deployment of this technology did not start until the 1990s (e.g., Curtis, 2002).

During or soon after hydraulic fracturing there may be an increase in fluid pressure along a fault plane, which, if critically stressed, can be reactivated inducing seismicity (Fig. 1a and b). A thorough review of the history of induced seismicity caused by a variety of mechanisms including hydraulic fracturing is timely as it places the magnitudes and frequency of hydraulic-fracturing-triggered seismicity into context. We introduce the theory behind how earthquakes are induced, review the context of global induced seismicity since 1929, and discuss the evidence that faults are being reactivated as a result of hydraulic fracturing and the processes by which this could be occurring.

1.1. Earthquakes

All rock masses that experience progressively changing stress are potentially seismogenic, i.e., capable of producing earthquakes. Progressive loading of stress by tectonic plate movements is the primary geological earthquake-inducing process. It results in intense deformation at the boundaries of plates, which are the most active earthquake zones. Plates are not absolutely rigid and the effect of their motions is transmitted into their interiors. There, lower-level, intraplate deformation occurs. This is sometimes localized in rift zones, e.g., the East African rift, and sometimes distributed throughout broad regions, e.g., Britain, mainland Europe, and the Basin and Range Province, western U.S.A. (Sykes and Sbar, 1973).

Fluids play a critical role in triggering seismicity in many different geological scenarios. Earthquake activity accompanies volcanic activity, and liquid magma is involved in those cases, e.g., at Yellowstone, USA. Occasionally, large earthquakes are accompanied by significant changes in groundwater, e.g., changes in the level of the water table. Usually, however, there is no direct evidence of fluid involvement. Nevertheless, fluids must lubricate fault surfaces that slip in earthquakes because otherwise friction on the fault plane would be too large to be overcome at the failure energy levels observed. This conjecture is supported by the absence of a large heat flow anomaly above the San Andreas fault zone, which would inevitably be generated by the friction of dry rock surfaces slipping past each other (Lachenbruch and Sass, 1980).

Artificially injecting fluids into the Earth’s crust induces earthquakes (e.g., Green et al., 2012). Fluid injection not only perturbs stress (Fig. 1b) (Scholz, 1990) and creates new fractures, but it also potentially introduces pressurised fluids into pre-existing fault zones, causing slip to occur earlier than it would otherwise have done naturally (Fig. 1a and b).

1.2. Earthquake sizes

Earthquakes range in magnitude from a maximum of ~10 down to arbitrarily small values. In the most sensitive microearthquake monitoring experiments, the lower magnitude limit of earthquakes that are reported is approximately M −3. Although traditional earthquake magnitudes are a familiar measure to most people, they are an empirical measure and no longer fit for modern purposes. They have thus been superseded by seismic moment, a measure that has physical meaning.

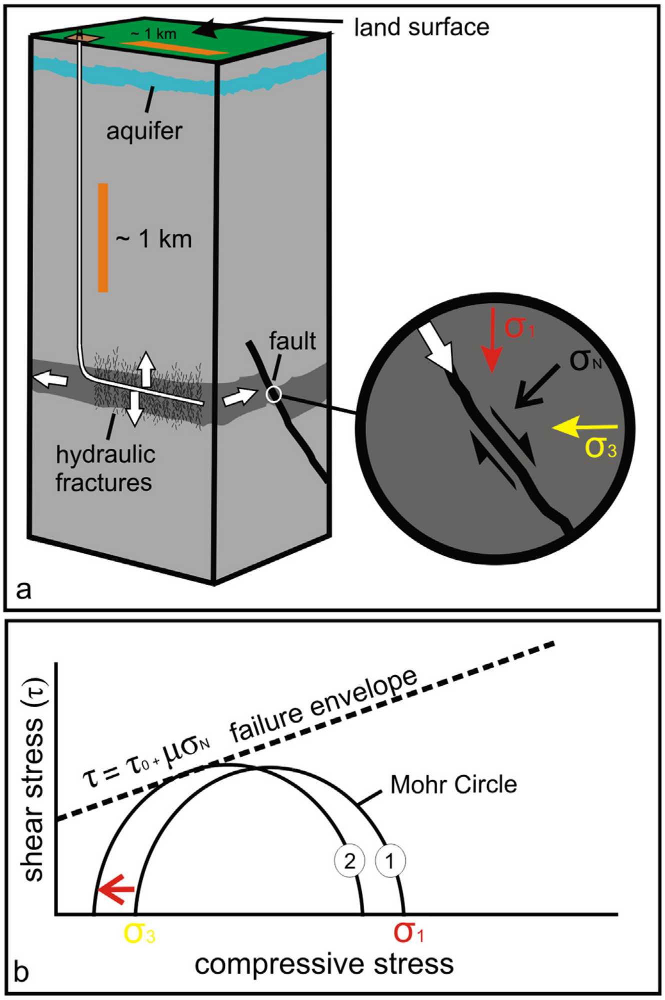

Figure 1. Induced seismicity caused by hydraulic fracturing. (a) Cartoon of a well drilled vertically and then horizontally into fine-grained, low-permeability strata (dark grey), which are offset by a normal fault (thick black line). Fluid, or a fluid pressure pulse, can be transmitted into a nearby or intersecting, critically stressed fault (white arrows). Compressive stresses σ_1, σ_2, and σ_3 act upon the fault. In this case σ_1 is depicted as being vertical, σ_2 is horizontal (out of the page and not shown), and σ_N is the normal stress acting on the fault plane. Failure occurs when the shear stress (τ) is higher than the sum of the shear strength (τo) and frictional stress on the fault plane ($\mu\sigma_N$), where μ is the coefficient of friction. (b) A Mohr diagram for the fault plane. Mohr Circle 1 represents σ_1 and σ_3 for the critically stressed fault plane prior to hydraulic fracturing. It is therefore located close to the Mohr failure envelope. During hydraulic fracturing, or during shut in of the well before flowback, the fluid pressure within the fault zone could increase. This could occur due to transmission of a fluid pressure wave or because hydraulic fracturing fluid or pore fluid enters the fault increasing fluid pressure. This causes a reduction in the compressive stress, σ_1 and σ_3, so the Mohr circle shifts to the left (red arrow, Mohr Circle 2), intersects the failure envelope, shear failure occurs, and if this is over a significant length of the fault, there is the potential for felt seismicity.

In the past, many magnitude scales were proposed to suit convenience in different situations, and several are still in widespread use. Magnitudes are calculated from measurements made directly from recorded seismograms, such as wave amplitudes or durations. Magnitude formulae usually take into account the epicentral distance of the earthquake from the recording station, but they ignore many other factors such as the hypocentral depth and the structure of the Earth between the source and the recorder. As a result, magnitude is not a measure of source physics, but of seismogram characteristics. Different magnitudes are typically obtained by analysing seismograms recorded at different seismic stations, or by