Possible Role of Progressive Aseismic In-Zone Failures in Generating Out-of-Zone Induced Seismicty

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Summary

Several incidents of seismicity induced by subsurface operations such as hydraulic fracturing and fluid flow disposal have been recorded in the geological settings other than the operational target zones. This behaviour has been usually justified by hypothesising that, first, the fault dislocations corresponding to these events initiate exactly at the locations of the recorded events and, second, these dislocations are directly triggered by the transmission of pore pressure and/or stress changes induced by subsurface operations. In here, it is argued that these changes might be less responsible for the out-of-zone seismic events and, perhaps, these events are induced by progressive aseismic in-zone fault failures that initiate within the target zone and lead to seismic rupture in distant seismogenic geological units. This argument seems to be able to explain both the spatial and temporal lags observed between the subsurface operations and the corresponding seismic events induced by them.

Introduction

During the last few years, frequent incidents of seismicity induced by fluid disposal and hydraulic fracturing operations has drawn undivided attention from the society, media, industry and politicians. Currently, a great volume of research activity is dedicated to understanding and explaining why these earthquakes are happening and how they can be prevented or mitigated. Among several challenges faced by the researchers in this field, the most fundamental one is understanding the causal sequence that results in generation of these seismic events. Although the traditional methods used to analyze induced seismicity are applicable to explaining some of the recorded seismic events, providing proper explanation for some of these earthquakes has appeared to be fairly challenging. In several cases, considerable spatial distances and/or time lags were recorded between the subsurface operations and seismic events. For intance, several of the seismic events induced by fluid disposal in the Arbuckle Formation in Oklahoma were recorded close to the basement faults (Walsh and Zoback, 2015). Seismic events induced by hydraulic fracturing in the Montney and Duvernay formations in the Western Canadian Sedimentary Basin (WCSB) are other examples of such behaviours as several of their recorded seismic events were located out of the target zones (BCOGC, 2014; Schultz et al., 2016). While some of the recorded events have been assigned to the depths shallower than the target zones, many of them have been located at the lower depths and sometimes as deep as the basement rocks. It has been reasonably argued that the significant uncertainties in the methodologies used for microseismic data processing might have led to the depth misinterpretation for these events. Nevertheless, until more accurate analyses confirm otherwise, the occurrence of these 'potentially' out-of-zone events cannot be simply ruled out based on this argument. In some cases, induced seismicity events were recorded days after the fracturing jobs (Bao and Eaton, 2016). In the following, potential mechanisms that might be responsible for these out-of-zone events are explored and discussed.

Background

The traditional concepts used to explain induced seismicity have been mostly developed around the assumption that the locations of the recorded seismic events are exactly where the fault failure or dislocation starts. Based on this assumption, at these locations, stress or pressure changes are significant enough to result in critical failure conditions necessary for fault reactivation. A substantial amount of poro-mechanical modelling has been developed to provide theoretical evidence for this potential mechanism. In several cases, these models have not been very successful in justifying fault reactivation in distant locations because stress changes usually diminish very quickly by moving away from the directly disturbed areas (i.e., injection zones or hydraulic fractures). Therefore, pore pressure change transmission has been usually considered to have a major role in fault reactivation. Fast lateral pressure change transmission is usually possible within lithologies with high permeability (e.g., in the case of fluid disposal). In the case of low permeability formations such as unconventional plays, fast lateral pore pressure transmission is only possible if permeable fracture networks exist. In the case of pore pressure change transmission between different geological units, permeable faults are usually assumed to be the main contributors to the pressure transmission process. In the first glance, pore pressure transmission through a permeable fault seems to be likely but for the reasons discussed below, existence of such a mechanism that results in considerable pressure change far deeper than the operational zone cannot be easily justified.

On the Possibility of Downward Pore Pressure Transmission through Faults

There are different reasons to argue that the scenario of downward pressure change transmission through the faults might not be very realistic. As our case studies, let's consider the seismicity induced by hydraulic fracturing in the Montney and Duvernay unconventional plays in the WCSB. In the case of the Duvernay Formation, seismic sensitivity has been more prevalent in the Fox Creek area where several significant events have been recorded since the start of hydraulic fracturing operations in the region (AER, 2016). The Montney Formation has shown to be seismically active in different regions such as Caribou, Beg, Graham, Altares, Septimus, and Dawson (BCOGC, 2014). In many of these regions, as a consequence of high hydrocarbon maturity, both of the Duvernay and Montney plays are highly over-pressured to an extent that pore pressure values with a depth gradient of higher than 18 kPa/m are not rare ocasions (e.g., Soltanzadeh et al., 2015). In both cases, the proximity of the recorded sesimic events to the WCSB tectonic belt is considered to have a great influence on the potential of induced seismicity (BCOGC, 2014). Practically, a combination of high tectonic in-situ stresses and formation pressure is expected to result in high seismic sensitivity of the faults and fractures that exist within these plays. In other words, critically-oriented fractures and fault in these plays are expected to easily slide even if only a small magintude of pore pressure or stress changes are introduced by subsurface operations. Nevertheless, as mentioned before, not all the recorded induced seismic events are located within these plays and many of them are believed to be located within the geological units above or below the target zones. For instance, in some cases, induced seismic activitiy recorded after fracturing in the Montney play are located in the geological units which are up to 700m deeper than this play (BCOGC, 2014). Unlike the Montney Formation, many of these distant units are expected to have normal pressure regimes. In the case of the Duvernay Formation, some seismic events are located in the upper Ireton Formation but several of them are sesnsed in the lower strata and close to the basement where, again, the pore pressure is expected to be normal and faults are assumed to be cemented (Schultz et al., 2016).

Considering the less likelihood for having significant induced out-of-zone stress changes, the occurence of these remote seismic events have been usually correlated to pore pressure change transmission through the exiting permeable faults (e.g., Schultz et al., 2016). The following statements try to argue that the downward pressure change transmission through the faults might not be as straightforward as it is usually assumed:

- If we assume that a fault is permeable and does not act as a hydraulic barrier, what has held the target zones (e.g., Montney and Duvernay in here) from the continous drainage of their extremely high pore pressure throughout the geological time?

- If we assume that a fault is permeable, knowing that several of the geological units between the target zone and the locations of induced seismicity are highly permeable and normally pressured, what can keep the pressure wave from lateral dissipation into the intermediate formations prior to transmision to the location of induced seismicity?

- The buoyant character of light hydrocarbon fluids (as in the Montney and Duvernay Formations) does not comply with the assumption of donward pressure transmission through the faults and geologhical units which are mostly saturated with saline. On the other hand, the upward transmission throuigh a permeable fault can be very likely.

With the reasons provided above, we may conclude that the chance of downward pore pressure transmission through the faults is low unless it is confirmed by geological evidence. Downward pressure transmission seems to be possible in a a less likely condition where fault's sealing character is gradually deminished by progressive downward fault failure while, at the same time, the transmitting fault is sealed against lateral pressure diffusion all the way down to the point of interest (i.e., lateral pressure diffusion is unlikely). Apparently, having these two conditions simultaneously seems to be less plausible. Assuming that pore pressure change transmission is less likely to be considered resposnible for the observed out-of-zone induced seimicity, a different potential mechanism is discussed below.

Possibility of Preceding In-Zone Aseismic Movements

Another fundamental question regarding out-of-zone seismic activity is: 'even if a significant pressure change can reach to the event's location and reactivates a fault, what will prevent the pressure change from dislocating the fault in the upper zones and most importantly within the highly-pressured target zone that needs a much lower energy for reactivation?' Naturally, by having a normal pore pressure, those parts of the faults located in the zones other than the fracturing target zones (e.g., Montney and Duvernay) are expected to be more resistant against slippage. In addition, the influence of induced stress changes on these fault segments is much lower within the distant geological units. Therefore, it seems that the out-of-zone events need to be preceded by in-zone fault reactivation. In other words, the recorded incidents of fault reactivation are not the initial slippages that a fault experiences but they are probably the consequences of preceding aseismic dislocations initiated within the target zone. Therefore, instead of assuming that the out-of-zone fault segments are driectly reactivated by pore pressure or stress change transmission, it can be hypothesized that, initially, the stress and pressure changes will result in aseismic fault movements within the operational zone and, then, in a progressive manner, the strain/stress fields generated by these movements are transfmitted to the other segments of the fault in the other seismogenic geological units. Assumption of aseismic slippage in the highly pressurized zones such as the Duvernay and Montney formations can be acceptable as these zones are calcareous and siliceous shales with a rather low brittle behaviour. Moreover, by opening the fault gap and reducing the chance of cementation, the high hydrocarbon saturation and pressure in these zones can significantly dampen the brittle behaviour of the potential rupture. Nevertheless, fault failure in other zones are more likely to have stick-slip or brittle behaviour and, consequently, show a seismogenic character.

According to this argument, the recorded seismic events in the less-pressurized and more brittle segments of the fault might be the consequences of aseismic movements that occur in its highly-pressurized segments located within the operational zones. This mechanism can be explained by stress transfer theory that studies the seismic cycles of static stress changes along the progressively slipping faults. This theory hypothesises that progressive steady slippage at the fault planes can transfer stresses to the seismogenic segemnts and result in seimicity (e.g., Stein et al., 1997). This behaviour is consistent with the observations showing that the slow slippage precedes and triggers the unstable rupture phase during earthquakes (e.g., Latour et al., 2013). In such a condition, slow dislocation creep in the operational zones will results in earthquake nucleation in the deeper portions of the faults which are more likely to experience sudden rupture. By assuming progressive failure behaviour, the temporal lags observed between the operational and seismic activities may also be explained (e.g., Perfettini and Avouac, 2004). Note that it is possible that the progressive fault failure also enhances pressure transmission through a previously sealed fault, a factor that can increase the chance of out-of-zone induced seismicity. In this case, even downward fast pressure transmission through the fault might become possible.

Conclusions

Although direct pore pressure and stress change transmissions are the common approaches to justify fault reactivation induced by subsurface operations, it seems that they can hardly explain the observed out-of-zone induced seismicity events, especially when they are located much deeper than the operational zones. Probably, a resoanble approach to explain these events is considering them as the consequences of the previously initiated aseismic dislocations in the target zone. These in-zone aseismic failures can result in earthquake nulceation and ultimate rupture in the other seismogenic zones. As a practical conclusion, the models developed for the explanation and predicion of the out-of-zone induced seismicity should be able to account for the progressive stress and deformarion transfer along the faults. In more inclusive studies, it would be also important to consider the possible role of mechanical interaction among different faults as a possible cause for induced seismicity.

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