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Induced seismicity and its implications for CO_2 storage risk

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Abstract

Seismicity induced by fluid injection and extraction is a widely observed phenomenon. These earthquakes can exceed magnitudes of M 6 and have the potential to impact on the containment, infrastructure and public perceptions of safety at CO_2 storage sites. We examine induced seismicity globally using published data from 75 sites dominated by water injection and hydrocarbon extraction to estimate the timing (relative to injection/extraction), locations, size range and numbers of induced earthquakes. Most induced earthquakes occur during injection/extraction (~70%) and are clustered at shallow depths in the region of the reservoir. The rates and maximum magnitudes of induced earthquakes generally increase with rising reservoir pressures, total fluid volumes and injection/extraction rates. The likelihood of an earthquake greater than or equal to a given magnitude being induced during injection is approximately proportional to the total volume of fluid injected/extracted, which appears to provide a proxy for changes in rock dynamics. If this observation holds for CO_2 storage sites, then we can expect the rates and maximum magnitudes of induced earthquakes to be significantly higher for commercial-scale operations (e.g., 50 Mt) than for pilot projects (e.g., 50 kt). In accord with these results the risks associated with induced seismicity may also rise with project size. Mitigation and monitoring measures at commercial-size sequestration sites, including installation of microseismic networks, public education on the expected seismicity and pressure relief wells, will be key for risk reduction.

Keywords: Induced seismicity; fluid injection; CO_2 storage; risk.

1. Introduction

Seismicity induced by fluid injection and extraction results from anthropogenic changes in the state of stress of the rock mass [1-16]. Increases in reservoir pressure arising from the injection of CO_2 have the potential to induce earthquakes mainly of small to moderate magnitude (M). Induced seismicity may pose risks to the successful completion of CO_2 storage projects if mitigation measures are not incorporated into site development programmes. These risks include; i) induced earthquakes may be felt by, and cause concern to, the local community; ii) induced

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earthquakes may result in damage to infrastructure at a storage site, to nearby facilities and/or urban areas, and; iii) induced earthquakes could rupture the primary CO_2 seal, allowing CO_2 to migrate towards the ground surface.

To mitigate the risks of induced seismicity to CO_2 storage projects the key factors that contribute to these risks must be identified [15]. In the absence of geomechanical data at potential CO_2 storage sites, which could be used to predict fault slip and are unlikely to be available during the early stages of site evaluation, one means of examining what factors influence induced seismicity is to analyse historical information from fluid injection/extraction sites. At the present time little induced seismicity information is available for CO_2 injection projects, and this paper details seismicity from the best 75 sites where water and hydrocarbons have been injected or extracted, respectively. The resulting database has been used to estimate the likely timing (relative to injection/extraction), locations, size range and numbers of induced earthquakes. The implications of these data for risk arising from induced seismicity at CO_2 storage sites are explored. The inferences drawn from these data regarding CO_2 storage projects are speculative because the database does not include information from CO_2 storage sites, and must be tested with new information (particularly from CO_2 injection sites). The results are neither intended to replace detailed geomechanical studies of CO_2 storage sites nor the installation of microseismic monitoring networks. Indeed, installation and monitoring of microseismic networks are likely to be important for understanding and mitigating the risks associated with induced seismicity due to CO_2 injection and storage.

2. Data and Methods

To characterize induced seismicity we have compiled data from 75 fluid injection and extraction sites worldwide from the published literature [e.g., 1-16]. This study updates previous compilations of induced seismicity data [e.g., 9, 11, 15] and includes a large body of new information published over the last six years [e.g., 1-5, 12-14]. The total fluid volumes at these sites, which range from 200 m^3 to 548 million m^3, were injected/extracted over time intervals of hours to 90 years and produced earthquakes with magnitudes up to M 7. These sites commonly involve the injection of water or brine (e.g. waste disposal, secondary recovery of hydrocarbons and hot dry rock geothermal systems) and/or the extraction of hydrocarbons. For each of these 75 sites, the data include details about their operation including, location and type of reservoir (e.g., waste injection, oil extraction), the depth of fluid injection/extraction, and the change in reservoir pressure resulting from injection or extraction, as well as details about the induced seismicity such as the magnitude and hypocentral location of the largest induced earthquakes (e.g., Figure 1). Of these 75 sites, 30 provide more detailed information such as the volume and rate of fluid injection/extraction, the duration and dates of injection/extraction, reservoir permeability, earthquake magnitude scaling relationships (e.g., *b*-value), and the rates, location and timing of induced earthquakes above detection thresholds of M -2 to 1. Information from these 30 sites is the primary focus of this paper.

Our analysis utilises induced earthquakes from both fluid injection and extraction sites. Earthquakes induced by injection and extraction typically occur in response to increases and decreases in reservoir pressure, respectively [e.g., 11]. Injection induced earthquakes are of most relevance to CO_2 storage projects and we have included as much injection information as possible in this study. The database includes information from three Hot Dry Rock (HDR) sites designed to create hydraulic fracturing. The well head pressures and rates of seismicity (and *b*-value) at these sites are typically higher than at sites where no hydraulic fracturing occurs [e.g., 14], however, the maximum magnitudes of earthquakes do not appear to be elevated at HDR sites. The inclusion of these sites in our sample data set has not increased the maximum magnitudes.

The volumes of fluid mobilized at injection sites are small (e.g., <1 million m^3) compared to what will be required for commercial CO_2 storage projects (e.g., >50 million m^3) and do not provide direct information about the sizes and numbers of induced earthquakes that could be expected for these larger storage projects. Induced seismicity resulting from large-scale fluid extraction (<548 million m^3) is consistent with induced seismicity from injection in that it suggests that larger earthquakes can be expected with increases in the total volume and injection rate (see section 3). The examples of induced seismicity due to extraction are therefore useful for understanding the potential magnitudes and rates of induced seismicity associated with larger volumes of CO_2 injection.

The data include a number of uncertainties and limitations which could significantly affect the interpretation and conclusions of this study. The five main uncertainties and limitations of the induced seismicity data are; i) poor accuracy of some earthquake locations, ii) poor reporting of intermittent injection or extraction, iii) a relatively high threshold magnitude of complete recording (i.e., small magnitudes may be missed) , iv) uncertainty about whether some of the larger earthquakes were induced by fluid injection/extraction (as opposed to other processes); and v) a sampling bias of the published induced seismicity data toward productive or large maximum magnitude earthquake sequences. Here we have used the published locations for induced earthquakes, which have variable accuracy, together with the reported duration of injection/extraction and completeness. The magnitude of completeness strongly influences the number and magnitude range of recorded earthquakes and varies between sites. This is primarily dependent on the numbers and locations of seismometers relative to the induced earthquakes; and the level of anthropogenic background noise. In Figure 1a, for example, both the minimum recorded magnitude (~M -1.3) and the decline in earthquake frequency below M -0.5 are interpreted to derive from incomplete sampling below about M -0.5.

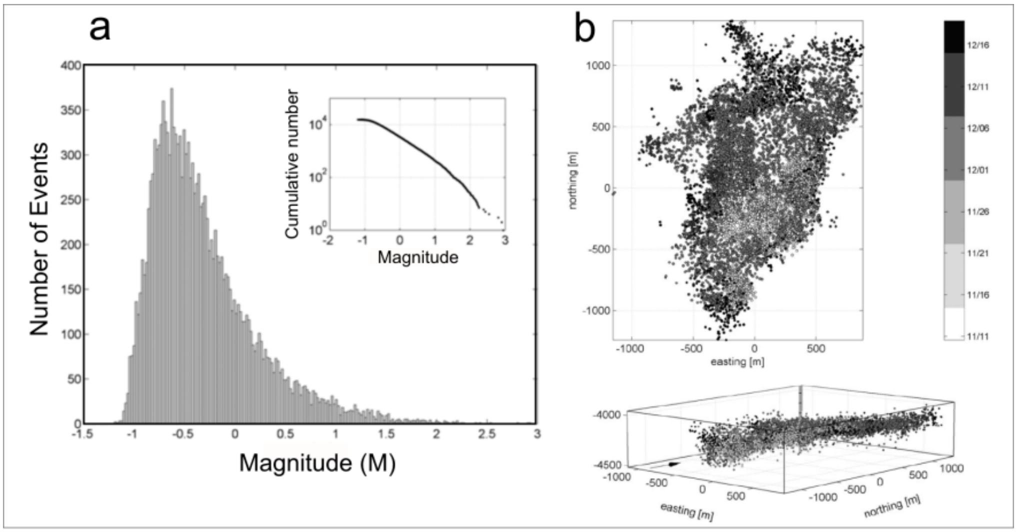

Figure 1. a) Magnitude-frequency distribution for induced earthquakes produced by injection 25,000 m^3 of water during the 2005 restimulation of the Cooper Basin reservoir, Australia [3]. b) Induced seismicity epi- (top) and hypo- (bottom) central locations with respect to the injection well (0,0) during the first hydraulic fracture experiment at Cooper Basin, Australia [2]. Timings of earthquakes with respect to the beginning of injection are colour coded and become increasingly darker with time following the onset of injection.

At many sites there is a strong indication that the seismicity is induced because the events are clustered about the reservoir and consisted of large numbers of small earthquakes at injection depths that persisted for as long as the pore pressures in the hypocentral region were elevated [e.g., 11](Figure 1b). In some cases the largest magnitude earthquakes (e.g., >M 5) may have been produced by processes other than fluid injection/extraction (e.g., tectonic activity). Such earthquakes are generally considered to be induced if: they are located proximal to, or within, the fluid injection/extraction reservoir; the measured or calculated state of stress in the crust exceeds (or is likely to exceed) the rock strength; the earthquakes occur during or immediately following injection/extraction; there is a clear temporal and/or spatial disparity between previous natural seismicity and the inferred induced events (e.g., background seismicity rates are very low). Using these criteria four large magnitude earthquakes (M 5-7) are inferred to have been induced by oil and gas extraction and have been included in our database. These earthquakes are: i) 1976 and 1984 M 7 Gasli, Uzbekistan, ii) 1983 M 6.5 Coalinga Eastside, California, USA, iii) 1985 M 6.1 Kettleman North Dome, California, USA and, iv) 1987 M 5.9 Montebello Fields, California, USA.

Lastly, the database utilised in this study is likely to be biased towards those sites where large magnitude earthquakes and high seismicity rates were recorded or were an expected outcome of injection. In some cases, for example, this bias towards sites with larger events may occur because dedicated seismometer networks were not installed at all injection/extraction sites. In such cases induced earthquakes would only have been detected on regional seismic arrays capable of recording larger earthquakes (e.g., >M 2) and sites with events below this threshold (including sites with little induced seismicity) would be excluded from the database. Figure 2 gives an indication of the potential for the bias by comparing the magnitude-frequency distribution of the entire data set, which has a mode of M 3.5, with the distribution from only the 30 best reported sites, which is skewed toward a higher maximum magnitude mode of M 4.5. This shift in mode is incorporated into the probability estimates in section 5.

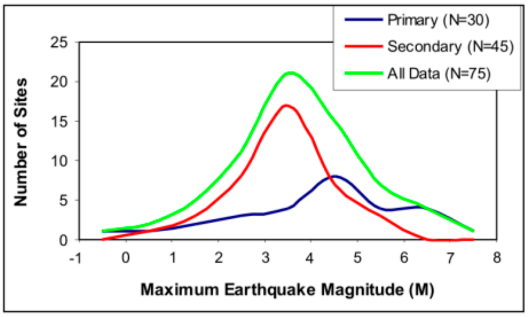

Figure 2. Frequency of maximum induced earthquake magnitudes. Data sets are; Primary, 30 best reported sites; Secondary, remaining 45 sites; All data, combined data set of 75 sites.

3. Factors Influencing Seismicity Magnitude and Frequency

The frequencies and magnitudes of induced earthquakes are thought to be dependent on a number of factors including; reservoir pressures and permeabilities, injection/extraction rates and the total volume of fluid introduced or removed from the system [e.g., 6, 7, 13, 14]. These relationships together with the timing and location of induced earthquakes have been examined using information from the best 30 sites.

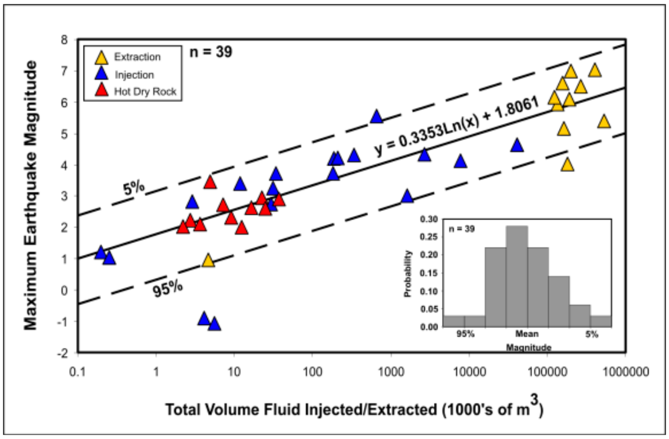

Figure 3. Maximum induced earthquake magnitude plotted against the total volume of fluid injected (blue filled triangles), extracted (yellow filled triangles) and Hot Dry Rock with hydraulic fracturing (red filled triangles) from the best 30 sites (some sites have multiple injection experiments). These sites have reservoir permeabilities of <1 D and injection/extraction rates of <100,000 m^3/day. The line of best fit was constructed using least squares regression on the y-axis and has an R^2=0.82. The 5% and 95% confidence intervals correspond to earthquake magnitudes of ±M 1.4 from the line of best fit. The inset histogram shows the distribution of magnitude misfit with the least squares fit as the mean.

The maximum induced earthquake magnitude is positively correlated to the total volume and rates of fluid injected/extracted, and to reservoir pressures and permeability. The best of these relationships is presented in Figure 3 where an exponential increase in fluid volumes correlates with maximum earthquake magnitudes. The spread of maximum magnitudes about the line of best fit is to be expected given uncertainties in the data, variations in stress conditions and pre-existing faulting between sites and the different types of operations (injection, extraction, HDR). The broad relationship is, however, consistent for both injection (HDR and storage projects) and extraction induced earthquakes, and does not change noticeably if the extraction events are excluded from the analysis. Therefore, it is proposed that injected and extracted fluid volumes provide a proxy for changes in sub-surface stress conditions. Figure 3 suggests that an order of magnitude increase in injected volume raises the mean expected maximum earthquake magnitude by approximately one magnitude unit, which could have significant implications for risk at CO_2 storage sites.

Productivity of induced seismicity is dependent on a number of factors including; injection/extraction rate and volume, and permeability of the rock volume influenced by operations [e.g., 14]. The *b*-value describes the relative numbers of small to large earthquakes in a given population, and typically has a value of approximately 1 for natural tectonic earthquakes and closer to 2 for seismicity induced by hydraulic fracturing [10]. A positive relationship between reservoir permeability and *b*-value has been observed for eight sites [e.g., 14]. Sites with very low permeabilities (e.g., <0.01 mD) display much higher *b*-values (~2.5) than sites with higher permeabilities (e.g., >0.01 mD; *b*-values 0.6-1.3). This relationship appears to be non-linear with the largest *b*-value increase occurring at permeabilities of <0.001 mD. This result is consistent with previous research from which it has been inferred that lower permeability reservoirs mainly deform by many small hydraulic fractures whereas earthquakes in higher permeability reservoirs typically reactivate pre-existing fractures [e.g., 10, 14]. Whatever the precise mechanism underlying the change in seismic productivity with permeability, it is accompanied by a change in reservoir pressures which, at individual sites, generally rise with seismic productivity [e.g., 14].

4. Location and Timing of Induced Seismicity

Predicting where and when induced earthquakes will occur is important for risk analysis. An earthquake soon after the onset of operations and close to an injector well may carry a higher risk to a CO_2 storage project than an event that occurs after completion of injection and distal to site infrastructure.

The depths of induced seismicity and injection are generally comparable with a tendency for induced seismicity to be, on average, slightly deeper than the reservoir interval. These deeper events may in some cases be induced by loading or unloading of the sub-reservoir rock volume by fluid injection or extraction, respectively. These conclusions apply equally to the largest earthquakes, which are randomly distributed within the depth range of seismicity for each site. Large magnitude earthquakes produced up to 10 km beneath large-scale hydrocarbon extraction sites (volumes >120 million m^3) are a notable exception to the above conclusions. The greater focal depths for some extraction-related earthquakes have been interpreted to be a direct reflection of the fact that extraction of large volumes of fluids has the potential to induce crustal-scale deformation and seismicity [e.g., 8, 9, 11]. Similar volumes of injected CO_2 have been proposed for commercial-scale CO_2 projects and could also load the crust and generate deep large magnitude earthquakes, although further research is required to test this hypothesis.

In map view earthquakes induced by fluid injection are generally clustered or form a halo around injector wells (Figure 1b). Clusters of induced earthquakes are typically well defined spatially and contain at least 95 % of the induced seismicity (Figure 1b). The maximum radius of induced seismicity is strongly correlated with the injected/extracted fluid volume (Figure 4a). Hence at individual sites, the maximum radius of seismicity increases over time with the total injected volume, although the dimensions and location of seismicity may not precisely describe the location of the injected-fluid plume. For example, limited information from six sites suggests that the maximum radius of the plume could be ≤50% of the maximum seismicity radius. One of the reasons for this difference is that the seismicity records the migration of the pressure front created by fluid injection or removal, which need not coincide with the margins of the plume. This difference may be particularly pronounced where the maximum radius of the seismicity is defined by reactivation of large pre-existing fault zones that extend outside the injected fluid plume [e.g., 1, 12].

The majority of induced seismicity occurs during injection, a conclusion that applies equally to the maximum magnitude earthquake data set and earthquakes of all magnitudes from the Soultz-sous-Forets and Basel sites (Figure 4b). The temporal distribution of induced seismicity is broadly similar for each data set, although the rates of seismicity can be more variable at individual sites. This similarity is consistent with the view that the timing of induced earthquakes is independent of earthquake magnitude and the duration of injection/extraction. Therefore, the larger composite data set (i.e., All Mag, Figure 4b) can be used to construct an empirical probability distribution function for the timing of the largest magnitude events for a proposed injection site (Figure 4b). The seismic response to fluid injection is not instantaneous but typically commences within hours or days of the onset of injection/extraction [e.g., 13, 14]. Approximately 70% of the induced earthquakes occur during the period of injection/extraction (normalised timing ≤1), with a further ~20% of the induced earthquakes occurring after operations cease between normalized times of 1 and 1.25. The remaining 10% of earthquakes occur over normalized times of up to 3.5 and produce a long relatively low seismic productivity tail to the temporal distribution. In accord with these proportions, and at sites where injection is continuous, the rate of seismicity is generally uniform during injection and declines exponentially after injection has been completed.

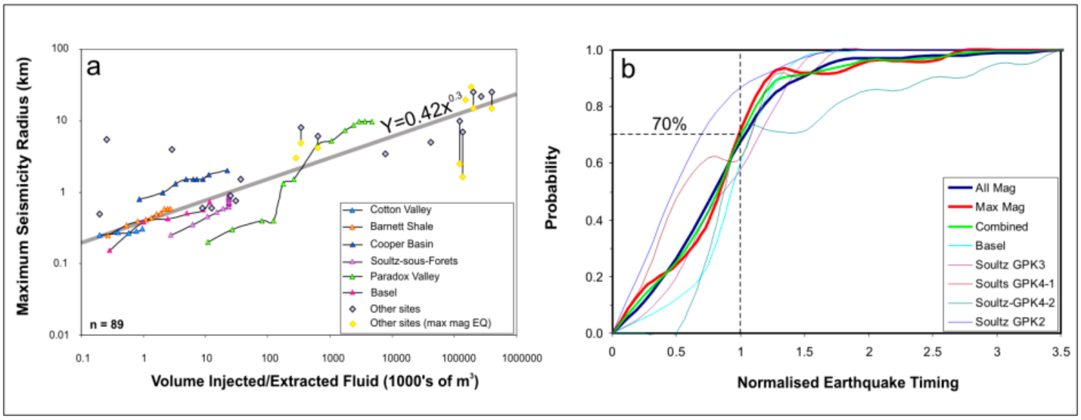

Figure 4 a) Maximum radius of induced seismicity from the injection well plotted against the volume of fluid injected at different stages of the injection operation for six sites, and against the total volume of fluid injected/extracted for an additional 16 sites where fluid volumes were not available at multiple stages of the operation. Data for Cotton Valley and Barnett Shale are from [14]; Cooper Basin from [3]; Basel from [7]; Paradox Valley from [1], and; Soultz-sous-Forets from [4]. Least squares line of best fit for all data. b) Timing of induced earthquakes relative to the onset (0) and completion (1) of injection/extraction. Probability is the cumulative number of earthquakes normalised by the total number of events. Basel and Soultz-sous-Forets data are from [7] and [5], respectively. Combined is all earthquakes from Basel and Soultz (N=489), Max Mag is the maximum magnitude earthquakes data from 25 sites (N=25) and All Mag (N=514) is Max Mag plus Combined.

5. Induced Seismicity and CO_2 Storage Risk

Fluid injection and extraction projects over the last 50 years suggest that the injection and long-term storage of CO_2 will produce induced seismicity [1-16]. This paper serves as a reminder that induced seismicity should be given consideration when planning and risking future CO_2 storage projects. In order to assess the risks to successful completion of CO_2 storage projects we require an understanding of the expected size, number, location and timing of induced earthquakes together with their likely impact on the storage container, infrastructure (both CO_2 storage and societal) and public perceptions of the safety of CO_2 storage projects. The magnitudes of earthquakes necessary to trigger each of the three risks listed above may vary between sites. Despite these variations natural earthquakes at shallow hypocentral depths (e.g., <3 km) are typically felt at magnitudes of ≥M 2, while damage to infrastructure and seal rupture may result from earthquakes with magnitudes of ≥M 3-4.

Risk assessment requires that we have some knowledge of the probability for the occurrence of a range of earthquake magnitudes arising from CO_2 injection. In particular, we may wish to determine what the likelihood is of injection producing earthquakes that are large enough to be felt, and cause damage or rupture the primary seal. If we accept the relations between maximum earthquake magnitude and total volume of injected/extracted fluid in Figure 3, and assume a *b*-value of 1, then each factor of 10 increase of total volume injected approximately raises maximum earthquake magnitude by M 1 and the total number of earthquakes by a factor of 10. These changes in the induced seismicity with total injected volume will produce dramatic differences in the frequency-magnitude relations for CO_2 storage pilot (e.g., 50 kt) and commercial (e.g., 50 Mt) projects. They are also likely to impact on the probability of occurrence of earthquakes of a given magnitude and the associated risks will rise with project size.

For example, using the maximum earthquake magnitudes in Figure 3 (but assuming that they over-estimate magnitude by M 1, Figure 2), assuming a b-value of 1, and that 70% of seismicity occurs during injection, the probabilities of an induced earthquake of magnitude ≥M 4 occurring during injection are as high as 10^{-3} and 10^{-1} for pilot and commercial projects, respectively. Because of the bias in the data towards sites with larger and more frequent earthquakes these probabilities are considered maxima.

The information on induced seismicity presented will probably be of greatest value for risk assessment where limited geological (e.g., reservoir permeabilities and rock strengths, and locations of pre-existing faults) and dynamic (i.e., reservoir stress magnitudes and orientations) information are available for potential CO_2 storage sites. At this early stage of investigations the data will, at best, provide a general impression of the maximal level of risk posed by induced seismicity, while also providing a mechanism for designing mitigation measures to reduce the risks. Experience suggests that these mitigation measures have the potential to reduce the risks significantly [e.g., 1] and may include; public education on the likelihood of induced earthquakes and their potential impact on CO_2 containment and private property, locating storage sites as far as possible from urban centres or major infrastructure, prioritising the understanding of the reservoir pressure regime, and/or maintaining reservoir pressures below fracture gradients using both injection and pressure relief wells. These mitigation measures will probably require installation of microseismic networks and down-hole pressure gauges.

The conclusions of the present study are based a number of inferences and are accompanied by a significant degree of uncertainty. Five areas of research require further investigation to improve our understanding of induced seismicity processes and the associated risks they pose to CO_2 storage projects. The requirement for more high quality data is a common theme that underpins most of these research topics which are listed below.

1) No induced seismicity data from CO_2 storage projects have been included in the present data set of 75 sites. The inferences drawn from existing data regarding CO_2 storage projects are speculative and must be tested as new induced seismicity information becomes available from these sites. To ensure that such data are collected it is recommended that microseismic networks (including down-hole instruments) are installed at all CCS sites prior to, during and following injection.

2) We combine different types of data (e.g., injection, extraction and HDR) in search of generic relationships between key CO_2 storage attributes (e.g., stored volume, injection rates, reservoir permeability), and the magnitude-frequency, locations and timing of induced earthquakes. While these different types of projects show similarities in their maximum earthquake magnitudes relative to fluid volumes and injection/extraction rates, the importance of hydraulic fracturing and reactivation of pre-existing faults varies between types of injection/extraction sites [e.g., 14]. These variations in the earthquake process may lead some to question the validity of the collective approach adopted here and requires further investigation.

3) Induced earthquakes reported in the literature are inferred to be biased towards sites where the maximum magnitudes and rates of seismicity are highest. The degree of this bias and its implications for the results of this study are not known. In addition to including information from new sites to the induced seismicity database, there may be value in exploring the use of statistical methods, such as regression with censored data and the theory of missing trials, to provide unbiased estimates of the induced earthquake population.

4) More induced seismicity data are required to reliably predict their magnitude-frequency relations, locations and timing for a range of CO_2 reservoir types, storage volumes and injection rates. This is particularly so for the relations of maximum earthquake magnitude versus fluid volumes (N=39)(Figure 3) and injection rates (N=39) and hypocentral depth versus injection depth (N=19). The depth data are too few to be statistically robust.

5) Commercial-scale storage projects are likely to require the injection of large volumes of CO_2 which could result in regional crustal loading and large magnitude induced earthquakes beneath CO_2 storage sites; as has been reported at large-scale hydrocarbon extraction projects [e.g., 8, 9, 11]. The possibility of induced seismicity arising from crustal loading is not routinely considered for CO_2 storage projects, which tend to focus on reservoir-scale pressure increases and whether they will reactivate pre-existing faults or produce new fractures. Consideration should be given to whether crustal loading is a viable model for the generation of earthquakes in response to CO_2 injection. If the model is valid, then extraction of brine may be required at some commercial-scale CO_2 storage sites to maintain the dynamic equilibrium of the crust and reduce the risks of larger magnitude induced seismicity.

6. Conclusions

Seismicity induced by injection presents a potential risk for CO_2 storage sites. Published data from 75 fluid injection and extraction sites have been examined to estimate the timing (relative to injection/extraction), locations, size range and numbers of induced earthquakes. The dataset is small, incomplete and probably bias towards sites with high maximum earthquake magnitudes and rates of seismicity and should be interpreted with caution. Most induced earthquakes occur during injection/extraction (~70%) and are clustered at injection depths in the region of the reservoir. The rates and maximum magnitudes of induced earthquakes generally increase with rising reservoir pressures, total fluid volumes and injection/extraction rates. The probability of an earthquake greater than or equal to a given magnitude occurring within the reservoir region during injection is approximately proportional to the total volume of fluid injected, which may be a reasonable first-order proxy for changes in sub-surface stress conditions. If these relations apply to CO_2 storage sites, then the rates and maximum magnitudes of induced earthquakes can be expected to be significantly higher at commercial-scale than for pilot-scale projects. The increasing number and maximum magnitude of induced earthquakes suggest that risks will also rise with project size and serve to highlight the potential need for mitigation measures at commercial-size sequestration sites.

7. References

[1] Ake J, Mahrer k, O'Connell D, Block L. Deep-Injection and Closely Monitored Induced Seismicity at Paradox Valley, Colorado. Bull. Seis. Soc. Am. 2005; 95: 664-683.

[2] Baisch S, Weidler R, Voros R, Wyborn D, de Graaf L. Induced Seismicity during the Stimulation of a Geothermal HFR Reservoir in the Cooper Basin, Australia. Bull. Seis. Soc. Am. 2006; 96: 2242-2256.

[3] Baisch S, Voros R, Weidler R, Wyborn D. Investigation of Fault Mechanisms during Geothermal Reservoir Stimulation Experiments in the Cooper Basin, Australia. Bull. Seis. Soc. Am. 2009a; 99: 148-158.

[4] Baisch S, Voros R, Rothert E, Stang H, Jung R, Schellschmidt R. A numerical model for fluid injection induced seismicity at Soultz-sous-Forets. Int. J. Rock Mech. Min. Sci. 2009b; 47: 405-413.

[5] Charlety J, Cuenot N, Dorbath L, Dorbath C, Haessler H, Frogneux M. Large earthquakes during hydraulic stimulations at the geothermal site of Soultz-sous-Forets. Int. J. Rock Mech. Min. Sci. 2007; 44: 1091-1105.

[6] Healy JH, Rubey WW, Griggs DT, Raleigh CB. The Denver Earthquakes: Science 1968; 161: 1301-1310.

[7] Ladner F, Haring MO. Hydraulic Characteristics of the Basel 1 Enhanced Geothermal System. Geothermal Resources Council Transactions 2009; 33: 199-203.

[8] McGarr A. On a possible connection between three major earthquakes in California and oil production. Bull. Seis. Soc. Am. 1991; 81: 948-970.

[9] McGarr A, Simpson D, Seeber L Case Histories of Induced and Triggered Seismicity. In: International Handbook of Earthquake and Engineering Seismology 2002; 81A: 647-661.

[10] Maxwell SC, Jones M, Parker R, Miong S, Leaney S, Dorval D, et al. Fault Activation During Hydraulic Fracturing: Society of Exploration Geophysicists Expanded Abstract 2009; 28: 1552.

[11] Nicholson C, Wesson RL. Triggered Earthquakes and Deep Well Activities. Pure Appl. Geophys. 1992; 139: 561-578.

[12] Seeber L, Armbruster JG, Kim, W-Y. A Fluid-Injection-Triggered Earthquake Sequence in Ashtabula, Ohio: Implications for Seismogenesis in Stable Continental Regions. Bull. Seis. Soc. Am. 2004; 94: 76-87.

[13] Shapiro SA, Dinske C, Kummerow J. Probability of a given-magnitude earthquake induced by a fluid injection: Geophys. Res. Lett. 2007; 34: L22314.

[14] Shapiro SA, Dinske C. Scaling of seismicity induced by nonlinear fluid-rock interaction. J. Geophys. Res. 2009; 114: B09307.

[15] Sminchak J, Gupta N. Aspects of induced seismic activity and deep-well sequestration of carbon dioxide. Environmental Geosciences 2003; 10: 81-89.

[16] Zoback MD, Harjes H-P. Injection-induced earthquakes and crustal stress at 9 km depth at the KTB deep drilling site, Germany. J. Geophys. Res. 1997; 102: 18477-18491.

8. Acknowledgements

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