Monitorización sísmica para una gestión segura de almacenamientos geológicos de CO_2: *La perspectiva del mundo académico*

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EXCELENCIA SEVERO OCHOA

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C.R. Ranero

Education

1987	Degree in Geology, Basque Country University, Bizkaia, Spain.
1993	PhD at Earth Sciences Institute CSIC awarded at Barcelona University.
1993	Senior Researcher at Geomar, Kiel, Germany.
2005	ICREA Research Professor at Marine Sciences Institute, Barcelona, Spain.
2007	Head of the Barcelona Center for Subsurface Imaging (20-25 scientists)

Publication peer-reviewed: >130 papers in top international journals (3-4 paper ≈ 1 PhD Thesis).

Leadership

- **Supervision** of 9 MSc works, 12 PhD works (+1 underway), and over 20 Post-docs.
- **Principal Investigator** of >15 Project & ~10 Industry contracts, Chief Scientist 12 cruises.

Reviewer

- **Reviewer** for EU, NSF-US, NERC-UK, RC-Norway, CONICYT-Chile, Ifremer, ANEP-Spain.
- **Evaluation for Tenure and Professorship** at several USA, UK and Germany research centres.
- **Reviewer for scientific journals**: Nature, Nature Geoscience, Science, JGR, GRL, Tectonics, GJI, G-cubed, Geology, Geophysics, EPSL, etc…

Awards and Prizes

- **Fellow** of the American Geophysical Union (2018)
- **Premio** Ciudat de Barcelona en Ciencias Medioambientales y de la Tierra (2019)
- **Member** of Academia Europaea (2020)

Tipos de eventos sísmicos

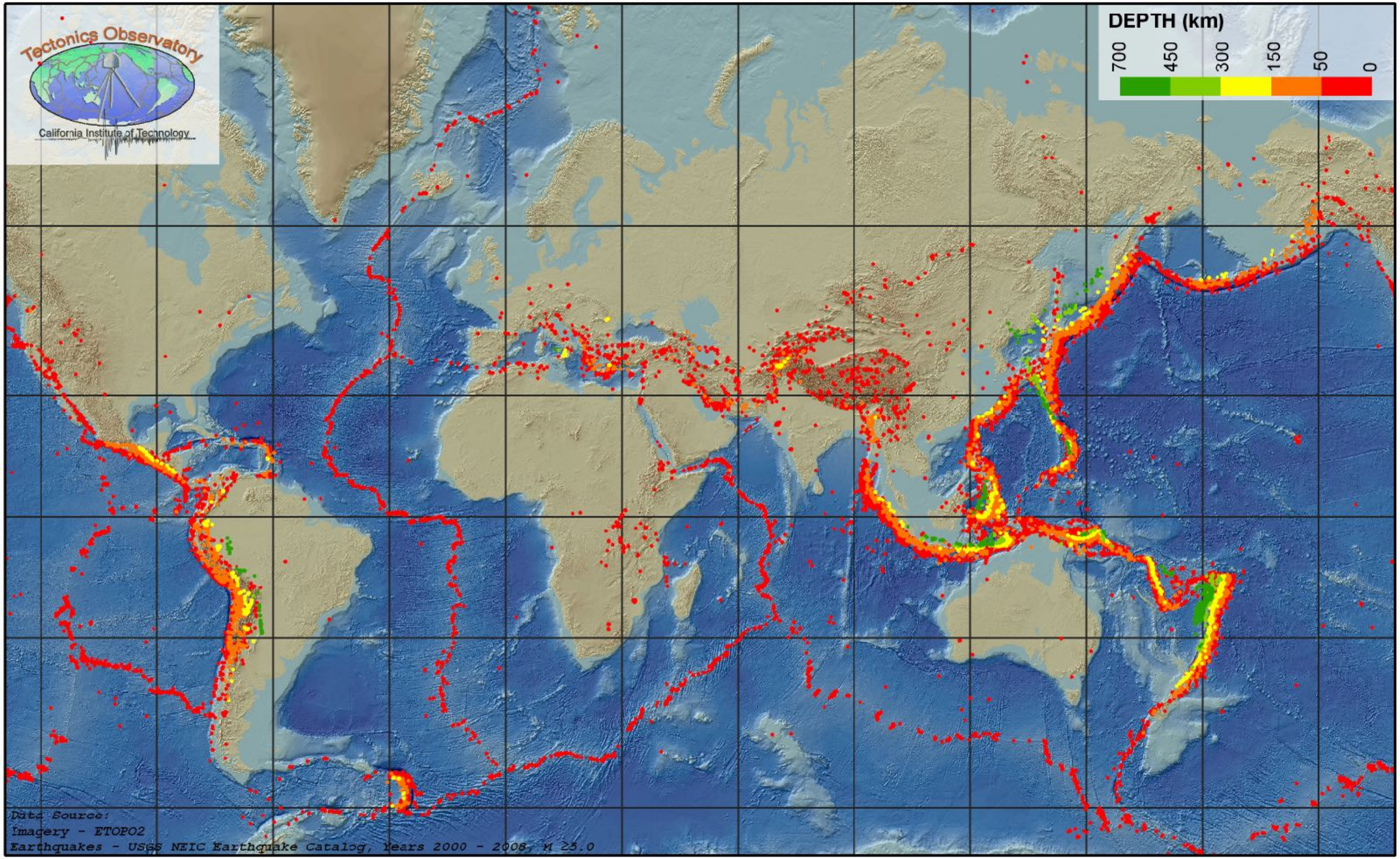
1. Natural:

- **Terremoto causado puramente por esfuerzos tectónicos.**

2. Antropogénico:

- **Disparado (*Triggered*): terremoto causado por esfuerzos tectónicos iniciados por la actividad humana.**
- **Inducido (*induced*): terremoto causado por esfuerzos relacionados directamente con la actividad humana.**

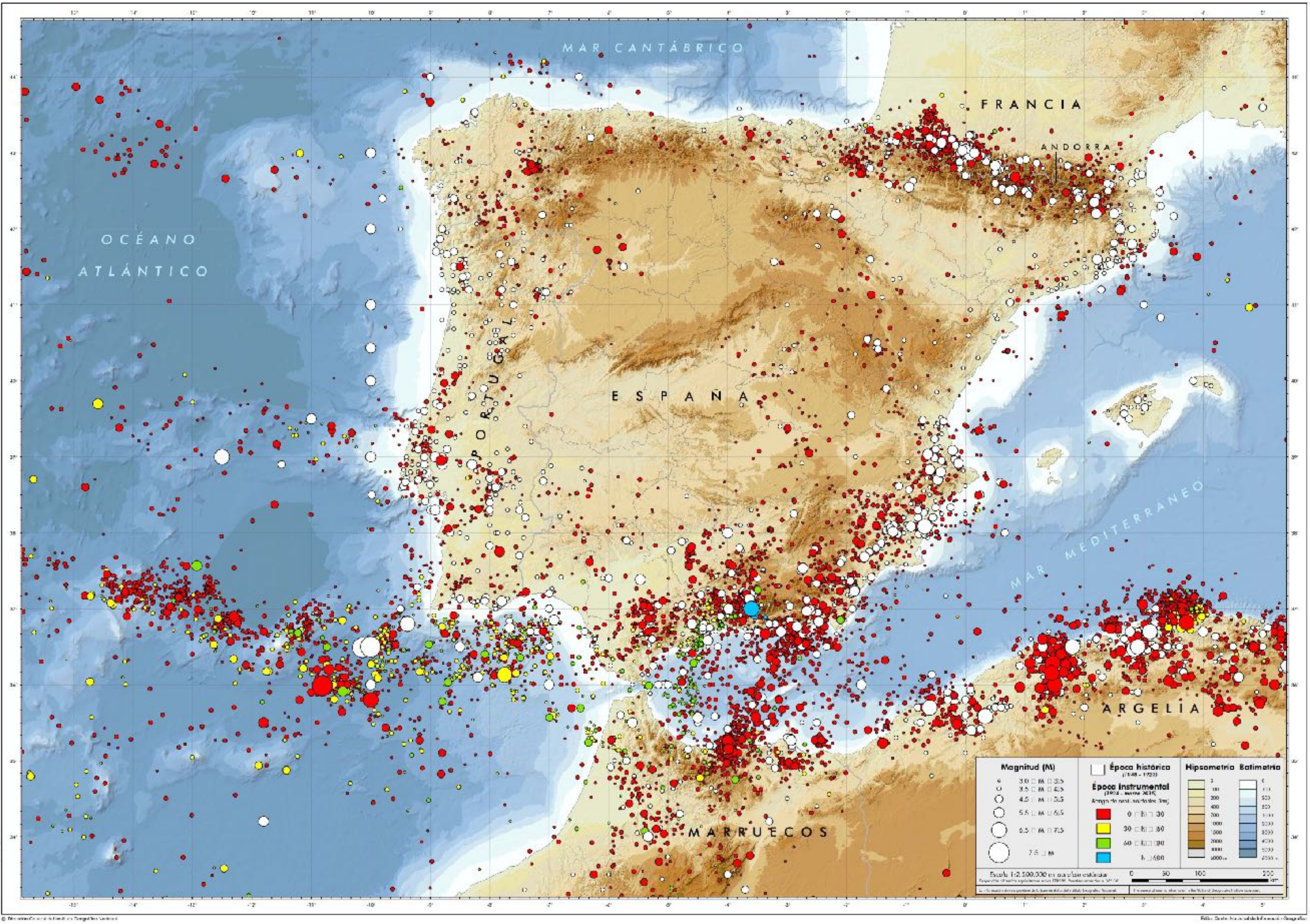
Sismicidad Natural



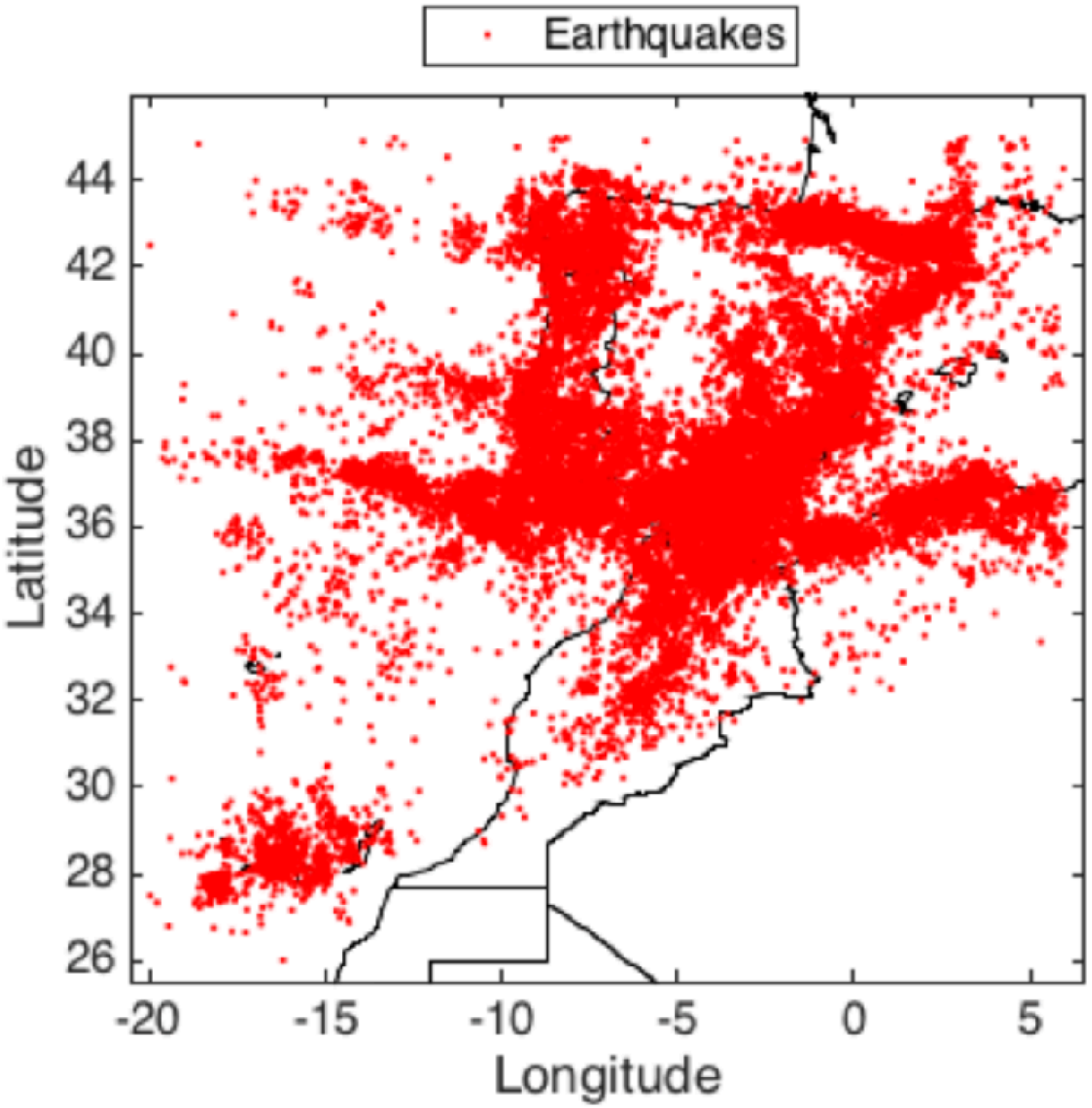
Data Source:
Imagery - ETOPO2
Earthquakes - USGS NEIC Earthquake Catalog, Years 2000 - 2008, M ≥5.0

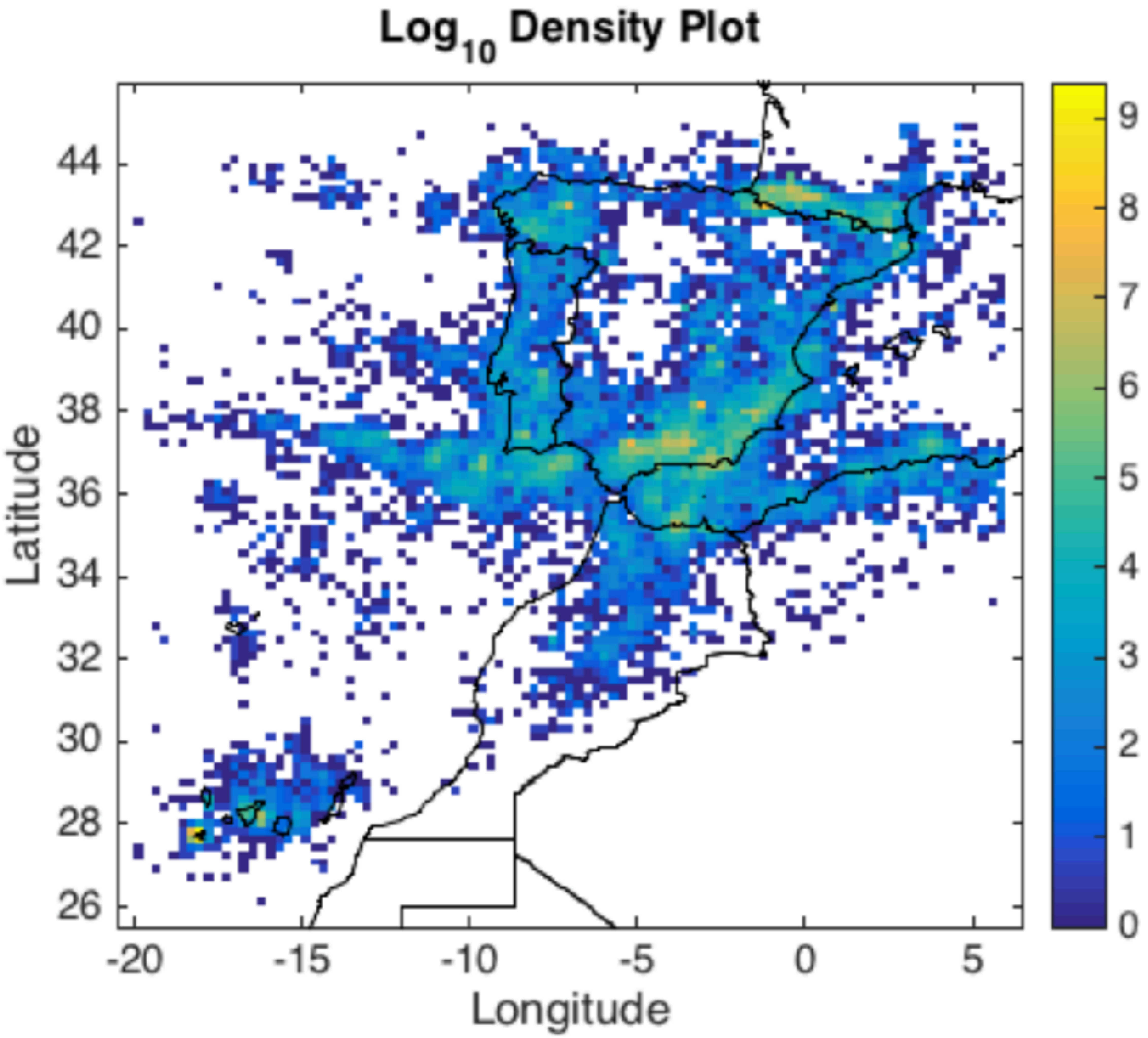
SISMICIDAD DE LA PENÍNSULA IBÉRICA Y ZONAS PRÓXIMAS

SEISMICITY OF THE IBERIAN PENINSULA AND NEIGHBORING ZONES



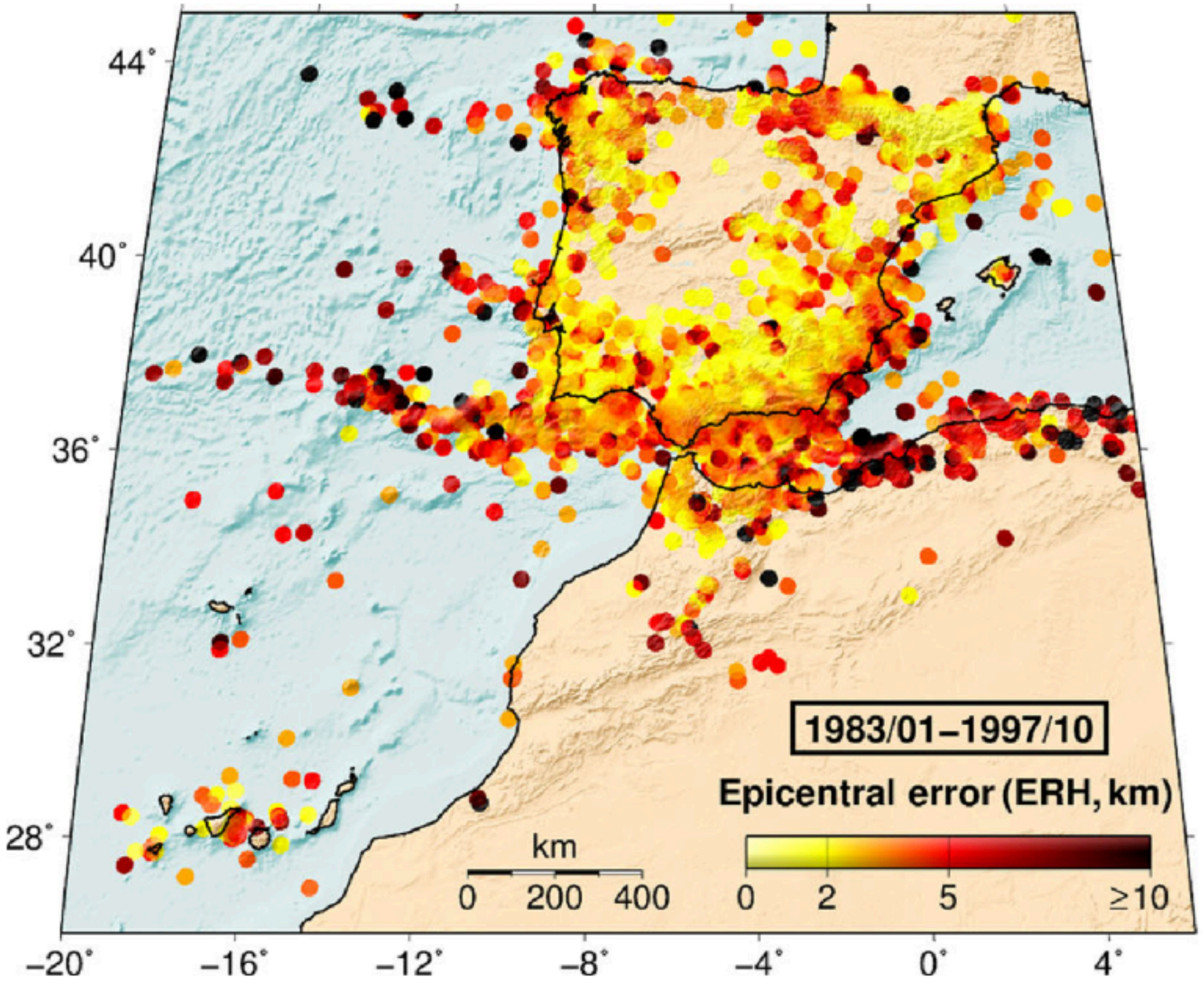
IGN catálogo: 1900-2015



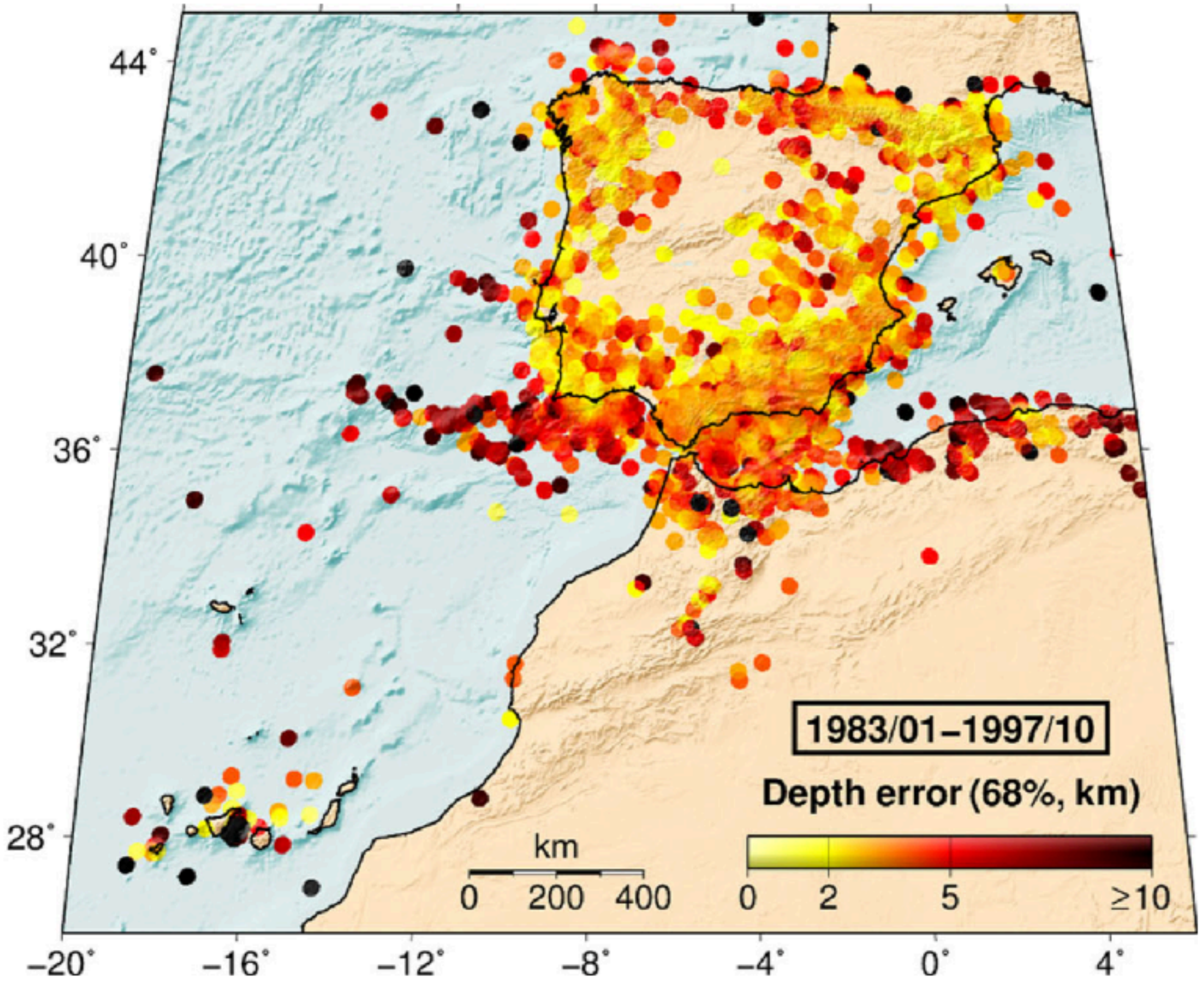


Número de terremotos: 103.831

Uncertainties/errors in epicenter and depthin the IGN catalog: 1983-1997



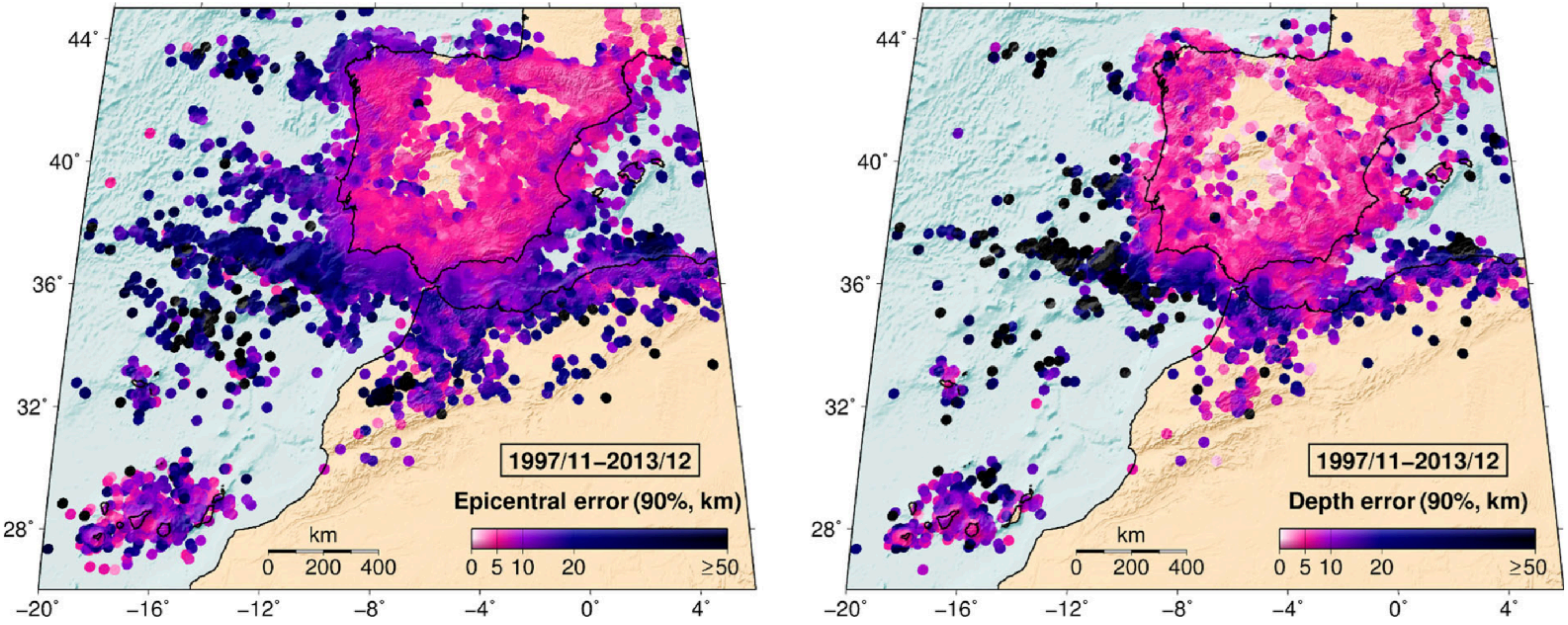
ERH



ERZ

González, J. Seismol. (2016)

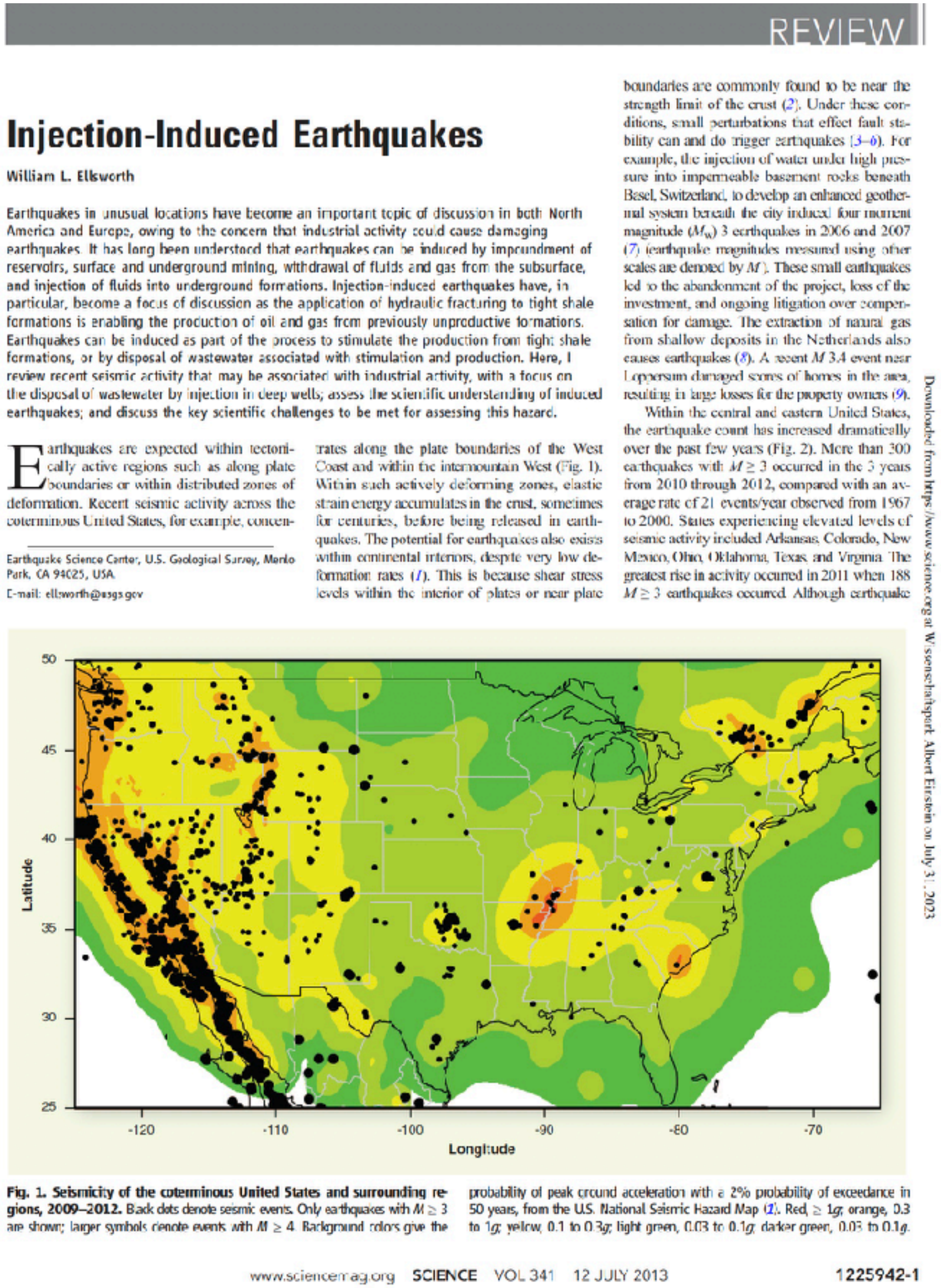
Uncertainties/errors in epicenter and depthin the IGN catalog: 1997-2013



González, J. Seismol. (2016)

Sismicidad Inducida

Mecanismos propuestos de la sismicidad inducida por inyección de fluidos



REVIEW

Injection-Induced Earthquakes

William L. Ellsworth

Earthquakes in unusual locations have become an important topic of discussion in both North America and Europe, owing to the concern that industrial activity could cause damaging earthquakes. It has long been understood that earthquakes can be induced by impoundment of reservoirs, surface and underground mining, withdrawal of fluids and gas from the subsurface, and injection of fluids into underground formations. Injection-induced earthquakes have, in particular, become a focus of discussion as the application of hydraulic fracturing to tight shale formations is enabling the production of oil and gas from previously unproductive formations. Earthquakes can be induced as part of the process to stimulate the production from tight shale formations, or by disposal of wastewater associated with stimulation and production. Here, I review recent seismic activity that may be associated with industrial activity, with a focus on the disposal of wastewater by injection in deep wells; assess the scientific understanding of induced earthquakes; and discuss the key scientific challenges to be met for assessing this hazard.

Earthquakes are expected within tectonically active regions such as along plate boundaries or within distributed zones of deformation. Recent seismic activity across the coterminous United States, for example, concentrates along the plate boundaries of the West Coast and within the intermountain West (Fig. 1). Within such actively deforming zones, elastic strain energy accumulates in the crust, sometimes for centuries, before being released in earthquakes. The potential for earthquakes also exists within continental interiors, despite very low deformation rates (*1*). This is because shear stress levels within the interior of plates or near plate boundaries are commonly found to be near the strength limit of the crust (*2*). Under these conditions, small perturbations that effect fault stability can and do trigger earthquakes (*3–6*). For example, the injection of water under high pressure into impermeable basement rocks beneath Basel, Switzerland, to develop an enhanced geothermal system beneath the city induced four moment magnitude (M_w) 3 earthquakes in 2006 and 2007 (*7*) (earthquake magnitudes measured using other scales are denoted by M). These small earthquakes led to the abandonment of the project, loss of the investment, and ongoing litigation over compensation for damage. The extraction of natural gas from shallow deposits in the Netherlands also causes earthquakes (*8*). A recent M 3.4 event near Loppersum damaged scores of homes in the area, resulting in large losses for the property owners (*9*).

Within the central and eastern United States, the earthquake count has increased dramatically over the past few years (Fig. 2). More than 300 earthquakes with $M \geq 3$ occurred in the 3 years from 2010 through 2012, compared with an average rate of 21 events/year observed from 1967 to 2000. States experiencing elevated levels of seismic activity included Arkansas, Colorado, New Mexico, Ohio, Oklahoma, Texas, and Virginia. The greatest rise in activity occurred in 2011 when 188 $M \geq 3$ earthquakes occurred. Although earthquake

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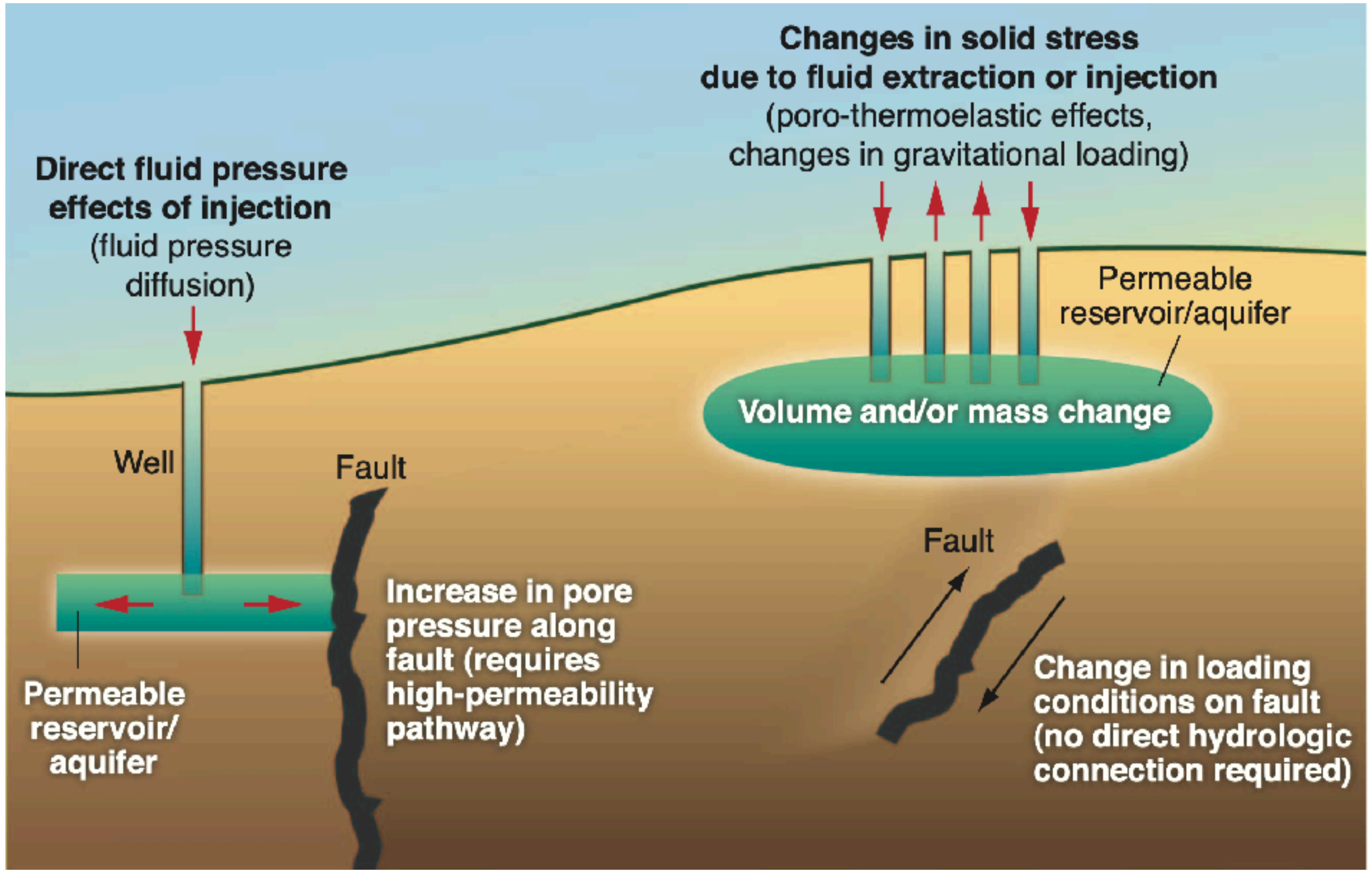
Fig. 1. Seismicity of the coterminous United States and surrounding regions, 2009–2012. Black dots denote seismic events. Only earthquakes with $M \geq 3$ are shown; larger symbols denote events with $M \geq 4$. Background colors give the probability of peak ground acceleration with a 2% probability of exceedance in 50 years, from the U.S. National Seismic Hazard Map (*1*). Red, ≥ 1*g*; orange, 0.3 to 1*g*; yellow, 0.1 to 0.3*g*; light green, 0.03 to 0.1*g*; darker green, 0.03 to 0.1*g*.



Ellsworth, Science (2013)

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Proceedings of the national Academy of Sciences (2012)

Proceedings of the national Academy of Sciences (2015)

Earthquake triggering and large-scale geologic sto
carbon dioxide

Mark D. Zoback[a,1] and **Steven M. Gorelick**[b]
Departments of [a]Geophysics and [b]Environmental Earth System Science, Stanford University, Stanford, CA 94305

Edited by Pamela A. Matson, Stanford University, Stanford, CA, and approved May 4, 2012 (received for review March 27, 2012)

Despite its enormous cost, large-scale carbon capture and storage (CCS) is considered a viable strategy for significantly red
associated with coal-based electrical power generation and other industrial sources of CO_2 [Intergovernmental Panel
(2005) IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovern
Climate Change, eds Metz B, et al. (Cambridge Univ Press, Cambridge, UK); Szulczewski ML, et al. (2012) *Proc Natl Aca*
5189]. We argue here that there is a high probability that earthquakes will be triggered by injection of large volumes o
rocks commonly found in continental interiors. Because even small- to moderate-sized earthquakes threaten the seal
repositories, in this context, large-scale CCS is a risky, and likely unsuccessful, strategy for significantly reducing greenh

carbon sequestration | climate change | triggered earthquakes

The combustion of coal for electrical power generation in the United States generates approximately 2.1 billion metric tons of CO_2 per year, ∼36% of all US emissions. In 2011, China generated more than three times that much CO_2 by burning coal for electricity, which accounted for ∼80% of its total emissions. (According to the Energy Information Agency of the US Department of Energy, total CO_2 emissions in China were 8.38 billion metric tonnes in 2011, with 6.95 billion tons from coal burning, nearly all of which is used electrical power generation.) From a global perspective, if large-scale carbon capture and storage (CCS) is to significantly contribute to reducing the accumulation of greenhouse gases, it must operate at a massive scale, on the order of 3.5 billion tons (1) of CO_2 per year, a volume roughly equivalent (2) to the ∼27 billion barrels of oil currently produced annually around the world. (Under reservoir conditions, one billion tons of CO_2 occupies a volume of ∼1.3 billion cubic meters, equivalent to 8.18 billion barrels. Thus, 3.5 billion tons of carbon dioxide would correspond to a volume of approximately 28.6 billion barrels. There are currently ∼850,000 wells producing oil around the world.) Moreover, a leak rate from underground CO_2 storage reservoirs of less than 1% per thousand years is required for CCS to achieve the same climate benefits as renewable energy sources (3).

Before embarking on projects to inject enormous volumes of CO_2 at numerous sites around the world, it is important to note that over time periods of just a few decades, modern seismic networks have shown that earthquakes occur nearly everywhere in continental interiors. Fig. 1, *Upper* shows instrumentally recorded earthquakes in the central and eastern United States and southeastern Canada. Fig. 1, *Lower* shows instrumentally recorded intraplate earthquakes in south and east Asia (4). The seismicity catalogs are complete to magnitude (M) 3. The occurrence of these earthquakes means that nearly everywhere in continental interiors a subset of the preexisting faults in the crust is potentially active in the current stress field (5, 6). This is sometimes referred to as the *critically stressed* nature of the brittle crust (7). It should also be noted that despite the overall low rate of earthquake occurrence in continental interiors, some of the most devastating earthquakes in history occurred in these regions. In eastern China, the M 7.8, 1976 Tangshan earthquake, approximately 200 km east of Beijing, killed several hundred thousand people. In the central United States, three M 7+ earthquakes in 1811 and 1812 occurred in the New Madrid seismic zone in southeast Missouri.

Because of the critically stressed nature of the crust, fluid injection in deep wells can trigger earthquakes when the injection increases pore pressure in the vicinity of preexisting potentially active faults. The increased pore pressure reduces the frictional resistance to fault slip, allowing elastic energy already stored in the surrounding rocks to be released in earthquakes that would occur someday as the result of natural geologic processes (8). This effect was first documented in the 1960s in Denver, Colorado when injection into a 3-km-deep well at the nearby Rocky Mountain Arsenal triggered earthquakes (9). Soon thereafter it was shown experimentally (10) at the Rangely oil field in western Colorado that earthquakes could be turned on and off by varying the rate at which water was injected and thus modulating reservoir pressure. In 2011 alone, a number of small to moderate earthquakes in the United States seem to have been triggered by injection of wastewater (11). These include earthquakes near Guy, Arkansas that occurred in February and

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that occurred in Augus
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Author contributions: M.D.Z. an
The authors declare no conflict
This article is a PNAS Direct Sub

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LETTER

No geologic evidence that seismicity causes fault leakage that would render large-scale carbon capture and storage unsuccessful

In a recent Perspective (1), Zoback and Gorelick argued that carbon capture and storage (CCS) is likely not a viable strategy for reducing CO_2 emissions to the atmosphere. They argued that maps of earthquake epicenters portray earthquakes occurring almost everywhere, suggesting that Earth's crust is near a critical state, so that increments in fluid pressure from injecting CO_2 at 1 to 3 km depth will likely trigger earthquakes within the reservoir and caprock that would be expected to result in leakage of CO_2 from the reservoirs to the surface.

Vast Majority of Earthquakes Are Much Deeper Than CO_2 Storage Reservoirs

Zoback and Gorelick (1) articulated an important, albeit well-known, concern: CCS may induce seismicity (e.g., ref. 2), as can other subsurface technologies (3). However, their characterization of seismic activity misrepresented its relevance to CCS. What is important is not epicenters (2D location on a map), but hypocenters (3D location, including depth). In fact, most hypocenters in the continental crust are in basement rock at 8 to 16 km depth (e.g., ref. 4), with only a very small fraction of them occurring in sedimentary cover at depths shallower than 3 km, where CO_2 would be stored. The rheological properties of shallow sedimentary formations usually allow them to undergo substantial deformation without establishing leaking pathways or localized faults, in contrast with brittle basement rocks.

Hydrocarbon Reservoirs Have Existed for Millions of Years in Regions of Intense Seismic Activity

Zoback and Gorelick (1) stated that seismic activity would compromise containment of the CO_2, and result in CO_2 leakage to the surface. For justification, they referred to laboratory studies on granitic rocks—conditions that are not relevant for CCS. In reality, large volumes of buoyant fluids have remained stable in geologic traps over millennia in regions experiencing strong and frequent earthquakes, like southern California, even under substantial overpressures. If ubiquitous earthquake-induced leakage occurred, there would not be large quantities of natural gas still present in the subsurface.

Site Selection Is Key

Although there are geologic settings in which induced earthquakes and leakage risk could compromise a CCS project (they mention the Mountaineer project), this says nothing about the many geologic formations that exhibit excellent promise for storing CO_2. Zoback and Gorelick (1) presented their conclusion that CCS will likely be unsuccessful without an analysis of the many suitable geologic formations available. In contrast, a recent study suggests that deep saline aquifers exist throughout the United States that can accommodate the CO_2 migration and pressure increases associated with large-scale injection at the century time scale (5).

Summary

The facts that sedimentary cover rarely is the source region for earthquakes and that shallow overpressured hydrocarbon reservoirs coexist with deep basement seismicity do not support Zoback and Gorelick's conclusion that moderate-size earthquakes necessarily threaten seal integrity to the point of rendering CCS unsuccessful (1). We do not argue that the issues they raised are immaterial, but, rather, that more work on the physics of induced seismicity, fault activation, and geologic characterization in the context of CCS is needed.

Ruben Juanes[a,1]***, Bradford H. Hager***[b]***, and Howard J. Herzog***[c]
[a]Department of Civil and Environmental Engineering, [b]Department of Earth, Atmospheric and Planetary Sciences, and [c]Massachusetts Institute of Technology Energy Initiative, Massachusetts Institute of Technology, Cambridge, MA 02139

1. Zoback MD, Gorelick SM (2012) Earthquake triggering and large-scale geologic storage of carbon dioxide. *Proc Natl Acad Sci USA* 109(26):10164–10168.
2. Cappa F, Rutqvist J (2011) Impact of CO2 geological sequestration on the nucleation of earthquakes. *Geophys Res Lett* 38:L17313.
3. National Research Council (2012) *Induced Seismicity Potential in Energy Technologies* (National Academy Press, Washington, DC).
4. Yang W, Hauksson E (2011) Evidence for vertical partitioning of strike-slip and compressional tectonics from seismicity, focal mechanisms, and stress drops in the East Los Angeles Basin Area, California. *Bull Seismol Soc Am* 101(3):964–974.
5. Szulczewski ML, MacMinn CW, Herzog HJ, Juanes R (2012) Lifetime of carbon capture and storage as a climate-change mitigation technology. *Proc Natl Acad Sci USA* 109(14):5185–5189.

Author contributions: R.J., B.H.H., and H.J.H. wrote the paper.
The authors declare no conflict of interest.

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Geologic carbon storage is unlikely to trigger large earthquakes and reactivate faults through which CO_2 could leak

Victor Vilarrasa[a,b,1] **and Jesus Carrera**[c]

[a]Earth Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720; [b]Soil Mechanics Laboratory, Ecole Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland; and [c]Grup d'Hidrologia Subterrània (GHS), Institute of Environmental Assessment and Water Research, Consejo Superior de Investigaciones Científicas, 08034 Barcelona, Spain

Edited by M. Granger Morgan, Carnegie Mellon University, Pittsburgh, PA, and approved March 25, 2015 (received for review July 13, 2014)

Zoback and Gorelick [(2012) *Proc Natl Acad Sci USA* 109(26):10164–10168] have claimed that geologic carbon storage in deep saline formations is very likely to trigger large induced seismicity, which may damage the caprock and ruin the objective of keeping CO_2 stored deep underground. We argue that felt induced earthquakes due to geologic CO_2 storage are unlikely because (*i*) sedimentary formations, which are softer than the crystalline basement, are rarely critically stressed; (*ii*) the least stable situation occurs at the beginning of injection, which makes it easy to control; (*iii*) CO_2 dissolution into brine may help in reducing overpressure; and (*iv*) CO_2 will not flow across the caprock because of capillarity, but brine will, which will reduce overpressure further. The latter two mechanisms ensure that overpressures caused by CO_2 injection will dissipate in a moderate time after injection stops, hindering the occurrence of postinjection induced seismicity. Furthermore, even if microseismicity were induced, CO_2 leakage through fault reactivation would be unlikely because the high clay content of caprocks ensures a reduced permeability and increased entry pressure along the localized deformation zone. For these reasons, we contend that properly sited and managed geologic carbon storage in deep saline formations remains a safe option to mitigate anthropogenic climate change.

carbon sequestration | induced seismicity | overpressure | climate change | CO_2 leakage

Zoback and Gorelick (1) claim that geologic carbon storage in deep saline formations is very likely to trigger induced seismicity capable of damaging the caprock, which could ruin the objective of keeping CO_2 stored deep underground. According to them, the main reason for this is that overpressure will be excessively high and failure conditions will be reached because the upper crust is critically stressed, i.e., close to failure. It is true that an excessive overpressure may induce microseismicity and even felt seismicity (2). It is also true that a felt seismic event could stop CO_2 sequestration projects, as happened with the geothermal project Basel Deep Heat Mining Project in Switzerland (3). However, there is no evidence from the existing CO_2 storage projects that CO_2 has the potential of easily inducing large earthquakes (4).

No felt seismic event has been reported to date at either pilot or industrial CO_2 storage projects (4–8). Even at In Salah, Algeria, where a huge overpressure was induced, no felt seismic event has been induced (7, 9). CO_2 storage in depleted gas fields has also been proven to be a safe option both at Otway, Australia (6) and at Lacq, France (5, 8). Actually, CO_2 storage operates under conditions similar to natural gas storage, which has not induced felt seismicity for decades (10–12). The recent induced seismic events at Castor, Spain (13) appears to be the only exception. However, too little is known about this site to extract any lesson. In fact, the very ignorance about what happened at Castor suggests that site understanding and management may be the critical issues.

We argue that large induced earthquakes related to CO_2 injection in deep saline formations are unlikely because (*i*) sedimentary formations are rarely critically stressed; (*ii*) the least stable conditions occur at the beginning of injection; (*iii*) CO_2 may dissolve at a significant rate, reducing overpressure; and (*iv*) brine will flow across the caprock, lowering overpressure in the reservoir. For these reasons we believe that geologic carbon storage in deep saline formations remains a safe option for mitigating climate change.

It Is Not True That the Whole Upper Crust Is Critically Stressed

It is generally accepted that the crystalline basement is critically stressed at some depth intervals (14–16). However, CO_2 will be injected in shallow (1–3 km deep) sedimentary formations, which are much softer than the brittle and stiff crystalline basement. As such, stress criticality, i.e., mobilized frictional coefficients, μ, in the range of 0.6–1.0 (17), is not usually observed at shallow depths within sedimentary formations (16, 18–21). We have compiled effective stress data of sedimentary formations and they fall within values of mobilized frictional coefficients around 0.4, i.e., the actual deviatoric stress is lower than the critical one (Fig. 1). This value is moderately low compared with the frictional coefficients around 0.6–0.8 of the critically stressed crystalline basement. In particular, the mobilized friction coefficients of sedimentary rocks where CO_2 is being, has been or is planned to be injected is always lower than the critical value of 0.6. This means that there is a wide margin before CO_2 injection might induce failure conditions and therefore, trigger a seismic event.

To illustrate that sedimentary formations are unlikely to be critically stressed, we have built a simple model of the upper

Significance

Geologic carbon storage remains a safe option to mitigate anthropogenic climate change. Properly sited and managed storage sites are unlikely to induce felt seismicity because (*i*) sedimentary formations, which are softer than the crystalline basement, are rarely critically stressed; (*ii*) the least stable situation occurs at the beginning of injection, which makes it easy to control; (*iii*) CO_2 will dissolve into brine at a significant rate, reducing overpressure; and (*iv*) CO_2 will not flow across the caprock because of capillarity, but brine will, which will reduce overpressure further. Furthermore, CO_2 leakage through fault reactivation is unlikely because the high clay content of caprocks ensures a reduced permeability and increased entry pressure along localized deformation zones.

Author contributions: V.V. and J.C. designed research; V.V. performed research; V.V. and J.C. analyzed data; and V.V. and J.C. wrote the paper.
The authors declare no conflict of interest.
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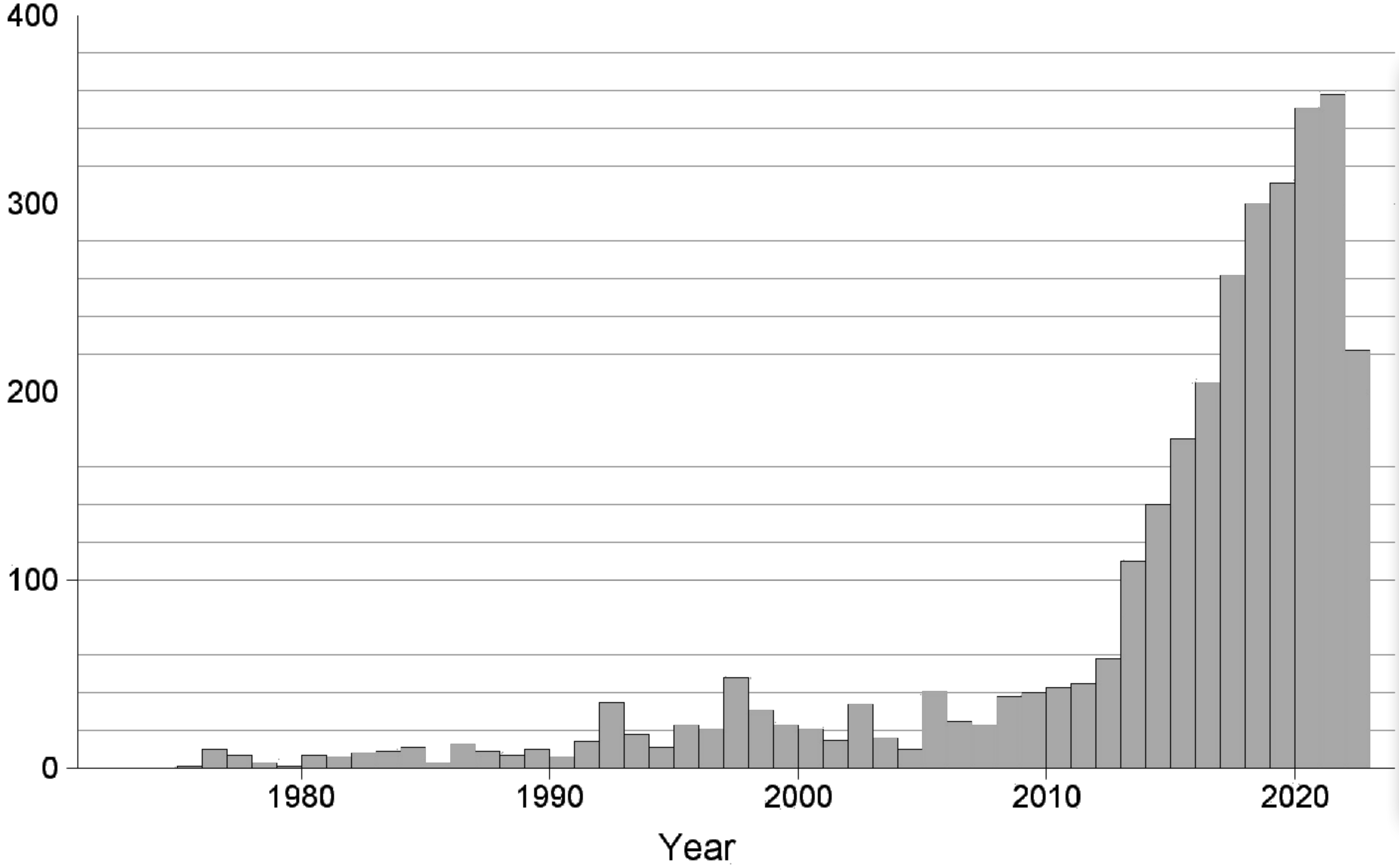
Yearly number of scientific papers on induced seismicity (2017)

Scientific Papers on Seismic Risk

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https://doi.org/10.1007/s10518-022-01357-4

ORIGINAL ARTICLE

Earthquake hazard and risk analysis for natural and induced seismicity: towards objective assessments in the face of uncertainty

Julian J. Bommer[1]

Received: 4 February 2022 / Accepted: 5 February 2022 / Published online: 20 April 2022

Abstract

The fundamental objective of earthquake engineering is to protect lives and livelihoods through the reduction of seismic risk. Directly or indirectly, this generally requires quantification of the risk, for which quantification of the seismic hazard is required as a basic input. Over the last several decades, the practice of seismic hazard analysis has evolved enormously, firstly with the introduction of a rational framework for handling the apparent randomness in earthquake processes, which also enabled risk assessments to consider both the severity and likelihood of earthquake effects. The next major evolutionary step was the identification of epistemic uncertainties related to incomplete knowledge, and the formulation of frameworks for both their quantification and their incorporation into hazard assessments. Despite these advances in the practice of seismic hazard analysis, it is not uncommon for the acceptance of seismic hazard estimates to be hindered by invalid comparisons, resistance to new information that challenges prevailing views, and attachment to previous estimates of the hazard. The challenge of achieving impartial acceptance of seismic hazard and risk estimates becomes even more acute in the case of earthquakes attributed to human activities. A more rational evaluation of seismic hazard and risk due to induced earthquakes may be facilitated by adopting, with appropriate adaptations, the advances in risk quantification and risk mitigation developed for natural seismicity. While such practices may provide an impartial starting point for decision making regarding risk mitigation measures, the most promising avenue to achieve broad societal acceptance of the risks associated with induced earthquakes is through effective regulation, which needs to be transparent, independent, and informed by risk considerations based on both sound seismological science and reliable earthquake engineering.

Keywords Earthquake hazards · Seismic hazard analysis · Seismic risk · Epistemic uncertainty · Induced seismicity · Seismic risk mitigation

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Sedimentary rocks at < ~2,5 km depth not critically stressed

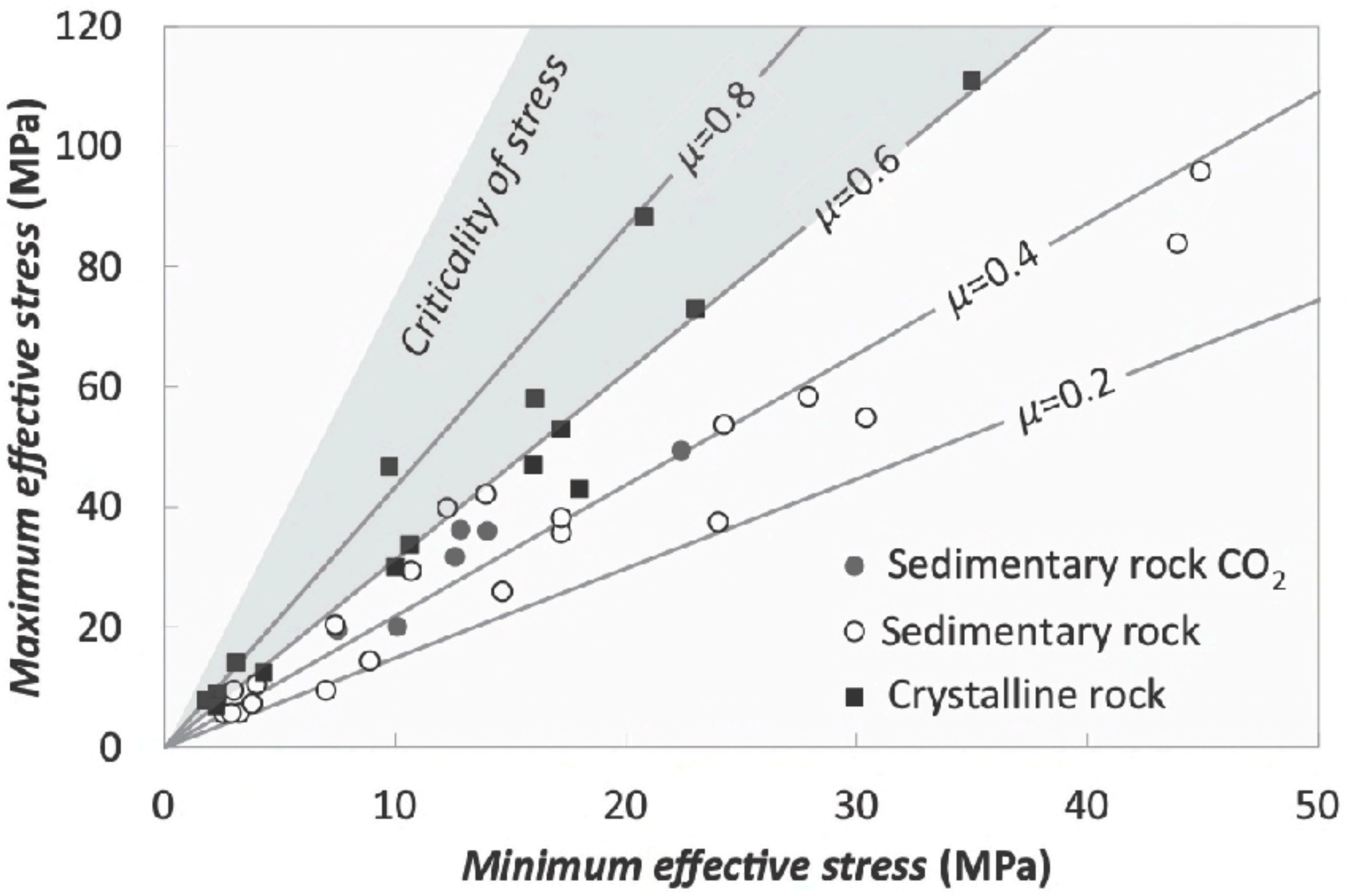


Fig. 1. Maximum versus minimum effective stress measured in wellbores at depth in both crystalline (black squares) and sedimentary rocks (hollow circles). Sedimentary rocks where CO_2 is being, has been or is planned to be injected are marked with black circles. The lines corresponding to several mobilized friction coefficients, μ, are included as a reference. Note that whereas crystalline rocks are critically stressed, sedimentary rocks are usually not.

Overpressures do not increase with CO2 injection

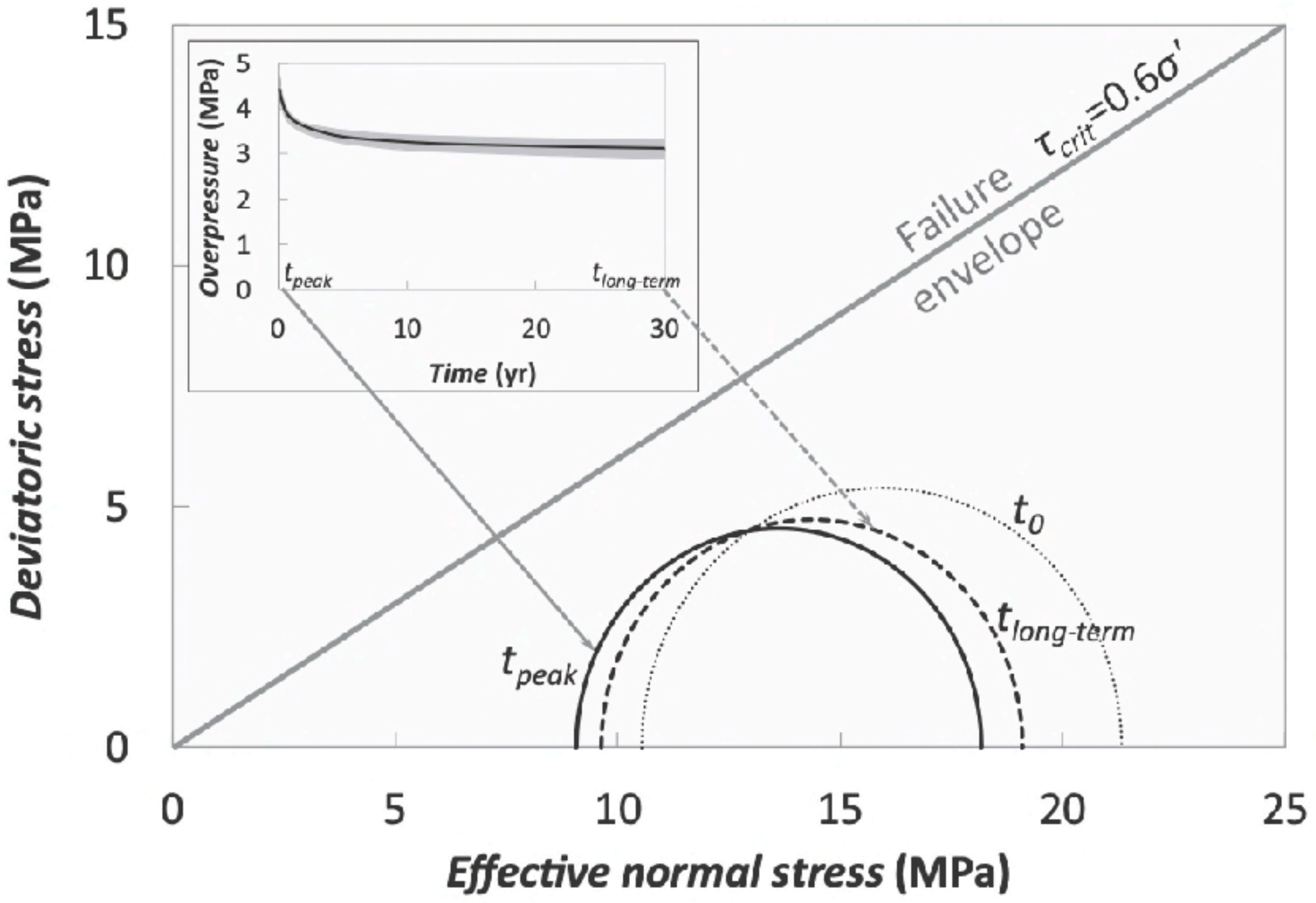


Fig. 3. Caprock stability and overpressure evolution in the reservoir at the injection well when injecting a constant mass flow rate of CO_2 (2 Mt/y) through a vertical well. The shadowed region in the inlet indicates the range of overpressures calculated by varying hydromechanical properties. Note that, initially, the stress state is far from failure conditions and that the less stable conditions occur at the beginning of injection.

Vilarrasa and Carrera (PNAS 2021)

The susceptibility to seismic reactivation

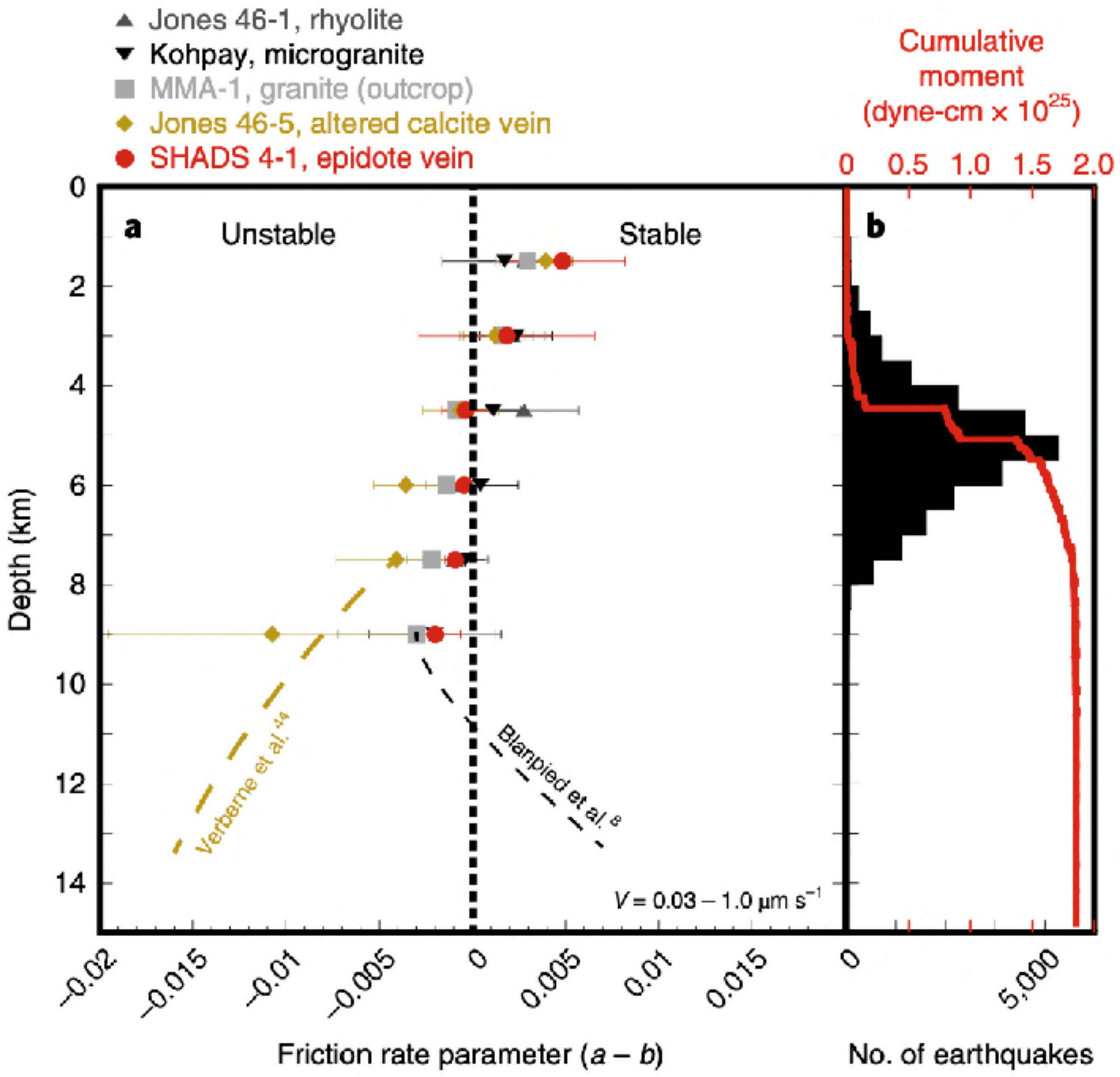


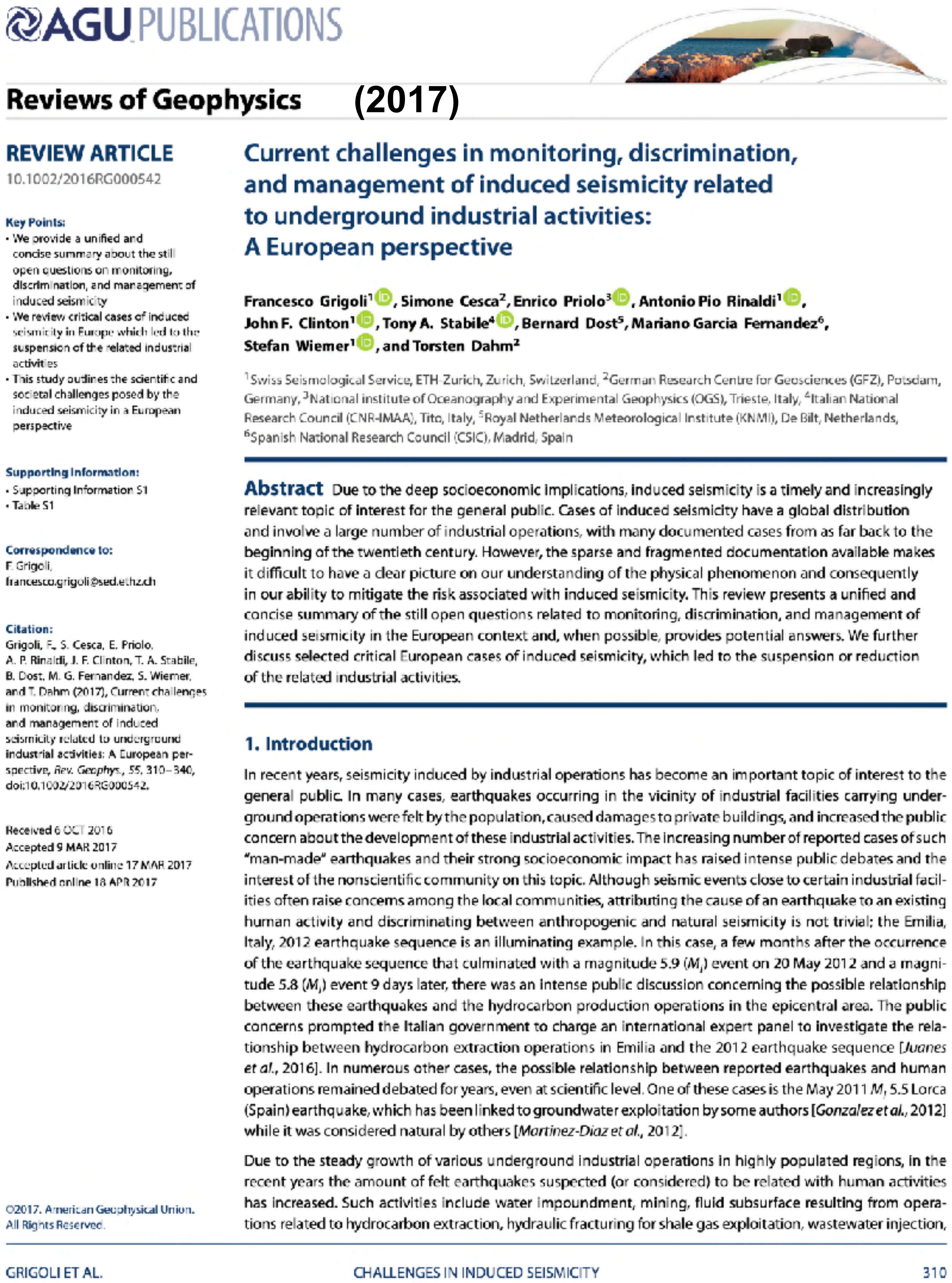
Fig. 4 | Depth distribution of seismic stability and earthquakes in Oklahoma. a, Seismic stability of Oklahoma basement samples as represented by the rate- and state-friction parameter ($a - b$). The symbol shows the average of the velocity steps tested, and the error bars show the range of values for each experimental sample and depth. Gold and black dashed lines represent projection of data for pure calcite[44] and Westerly granite[8], respectively. **b**, Histogram and cumulative moment[45] with depth for the relocated Oklahoma earthquakes (this study) for the period 2010–2017.

Kolawole et al., (Nature Geos. 2019)

Proyectos de Inyección de CO_2 en formaciones salinas

Proyecto	Masa Mt/duración	Sismicidad inducida
Quest, Canada	4 (2015-presente)	-0.9 to 0.2
Illinois Basin Decatur Project, USA	1 (2011-2014)	-1.1 to 1.3
Illinois Industrial CCUS Project, USA	1.7 (2017-presente)	-2.1 to 0.80
Sleipner, Norway	17.8 (1996-presente)	No red local/No sismicidad
Snøhvit, Norway	5.8 (2008-presente)	No red local/No sismicidad
In Salah, Algeria	3.8 (2004-2011)	0.05 to 1.7
Cranfield Saline Storage, USA	0.5 (2009-2010)	No red local/No sismicidad

La evolución de la visión académica



AGU PUBLICATIONS

Reviews of Geophysics **(2017)**

REVIEW ARTICLE

10.1002/2016RG000542

Current challenges in monitoring, discrimination, and management of induced seismicity related to underground industrial activities: A European perspective

Francesco Grigoli[1], **Simone Cesca**[2], **Enrico Priolo**[3], **Antonio Pio Rinaldi**[1],
John F. Clinton[1], **Tony A. Stabile**[4], **Bernard Dost**[5], **Mariano Garcia Fernandez**[6],
Stefan Wiemer[1], **and Torsten Dahm**[2]

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Key Points:

- We provide a unified and concise summary about the still open questions on monitoring, discrimination, and management of induced seismicity
- We review critical cases of induced seismicity in Europe which led to the suspension of the related industrial activities
- This study outlines the scientific and societal challenges posed by the induced seismicity in a European perspective

Supporting Information:

- Supporting Information S1
- Table S1

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Abstract Due to the deep socioeconomic implications, induced seismicity is a timely and increasingly relevant topic of interest for the general public. Cases of induced seismicity have a global distribution and involve a large number of industrial operations, with many documented cases from as far back to the beginning of the twentieth century. However, the sparse and fragmented documentation available makes it difficult to have a clear picture on our understanding of the physical phenomenon and consequently in our ability to mitigate the risk associated with induced seismicity. This review presents a unified and concise summary of the still open questions related to monitoring, discrimination, and management of induced seismicity in the European context and, when possible, provides potential answers. We further discuss selected critical European cases of induced seismicity, which led to the suspension or reduction of the related industrial activities.

1. Introduction

In recent years, seismicity induced by industrial operations has become an important topic of interest to the general public. In many cases, earthquakes occurring in the vicinity of industrial facilities carrying underground operations were felt by the population, caused damages to private buildings, and increased the public concern about the development of these industrial activities. The increasing number of reported cases of such "man-made" earthquakes and their strong socioeconomic impact has raised intense public debates and the interest of the nonscientific community on this topic. Although seismic events close to certain industrial facilities often raise concerns among the local communities, attributing the cause of an earthquake to an existing human activity and discriminating between anthropogenic and natural seismicity is not trivial; the Emilia, Italy, 2012 earthquake sequence is an illuminating example. In this case, a few months after the occurrence of the earthquake sequence that culminated with a magnitude 5.9 (M_l) event on 20 May 2012 and a magnitude 5.8 (M_l) event 9 days later, there was an intense public discussion concerning the possible relationship between these earthquakes and the hydrocarbon production operations in the epicentral area. The public concerns prompted the Italian government to charge an international expert panel to investigate the relationship between hydrocarbon extraction operations in Emilia and the 2012 earthquake sequence [*Juanes et al.*, 2016]. In numerous other cases, the possible relationship between reported earthquakes and human operations remained debated for years, even at scientific level. One of these cases is the May 2011 M_w 5.5 Lorca (Spain) earthquake, which has been linked to groundwater exploitation by some authors [*Gonzalez et al.*, 2012] while it was considered natural by others [*Martinez-Diaz et al.*, 2012].

Due to the steady growth of various underground industrial operations in highly populated regions, in the recent years the amount of felt earthquakes suspected (or considered) to be related with human activities has increased. Such activities include water impoundment, mining, fluid subsurface resulting from operations related to hydrocarbon extraction, hydraulic fracturing for shale gas exploitation, wastewater injection,

GRIGOLI ET AL. CHALLENGES IN INDUCED SEISMICITY 310

Nature 2021

Article

A process-based approach to understanding and managing triggered seismicity

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Bradford H. Hager[1,2,3], James Dieterich[2], Cliff Frohlich[3], Ruben Juanes[4,5], Stefano Mantica[6], John H. Shaw[7], Francesca Bottazzi[6], Federica Caresani[6], David Castineira[4], Alberto Cominelli[6], Marco Meda[6], Lorenzo Osculati[6], Stefania Petroselli[6] & Andreas Plesch[7]

There is growing concern about seismicity triggered by human activities, whereby small increases in stress bring tectonically loaded faults to failure. Examples of such activities include mining, impoundment of water, stimulation of geothermal fields, extraction of hydrocarbons and water, and the injection of water, CO$_2$ and methane into subsurface reservoirs[1]. In the absence of sufficient information to understand and control the processes that trigger earthquakes, authorities have set up empirical regulatory monitoring-based frameworks with varying degrees of success[2,3]. Field experiments in the early 1970s at the Rangely, Colorado (USA) oil field[4] suggested that seismicity might be turned on or off by cycling subsurface fluid pressure above or below a threshold. Here we report the development, testing and implementation of a multidisciplinary methodology for managing triggered seismicity using comprehensive and detailed information about the subsurface to calibrate geomechanical and earthquake source physics models. We then validate these models by comparing their predictions to subsequent observations made after calibration. We use our approach in the Val d'Agri oil field in seismically active southern Italy, demonstrating the successful management of triggered seismicity using a process-based method applied to a producing hydrocarbon field. Applying our approach elsewhere could help to manage and mitigate triggered seismicity.

The Val d'Agri field in southern Italy is the largest onshore oil field in western Europe and lies within a region of ongoing tectonic activity (Methods). Management of field operations is complicated by the need to dispose of the formation water that is associated with hydrocarbon production without triggering hazardous seismic activity.

Reinjection of co-produced formation water into the Costa Molina 2 (CM2) well to the southeast of the field commenced on 1 June 2006. Although seismic events were almost absent near the CM2 well before injection, the Eni network (Methods) began detecting microseismicity within a few hours after injection started, recording 69 events within 10 days (Extended Data Fig. 1) and around 300 very small events (maximum local magnitude (M_L) 2.2; too small to be felt) within 5 km of the well until the end of our study in June 2019. This seismicity, which displays alternating intervals of activity and quiescence, developed along a previously unidentified minor fault that we now call the Costa Molina fault (CMF)[5,6], with nearly all of the events located within the Apulian carbonates.

The clear association between the beginning of injection into the CM2 well and the onset of seismicity illuminating the CMF indicates that this seismicity is triggered. This raises both scientific and reservoir-management questions, including what rates of injection are safe and whether earthquakes are likely to be triggered on major faults. The unusually good knowledge of background tectonic stress, surface deformation, subsurface structure, fluid pressure, and forcing by known volumes of produced and injected fluids make the Val d'Agri field a unique natural laboratory, far surpassing what was available for the seminal Rangely study[4] and offering the potential for substantial advances in earthquake science and field management.

Our approach to understanding and managing this triggered seismicity is process based, with inputs from geology, geodesy, seismology, coupled flow and geomechanics models, and models of earthquake source physics. We calibrate these models based on observations up until 2016, arriving—from multiple modelling approaches—at predictions of injection rates that prevent pressures on the CMF from exceeding previous maxima. Microseismic monitoring after these predictions were made enables us to validate our approach. What sets this study apart is the use of a physics-based approach in a high-fidelity three-dimensional representation of the subsurface, first to reproduce observed seismicity rates and moment release caused by fluid injection, and second to forecast and successfully manage injection-induced seismicity, and to do so in an active oil field in a seismically active region.

The Val d'Agri field

The Val d'Agri oil field in the southern Apennines lies beneath a Quaternary-period basin bounded by the Monti della Maddalena and Eastern Agri fault systems (Fig. 1). During the Mesozoic era to the early

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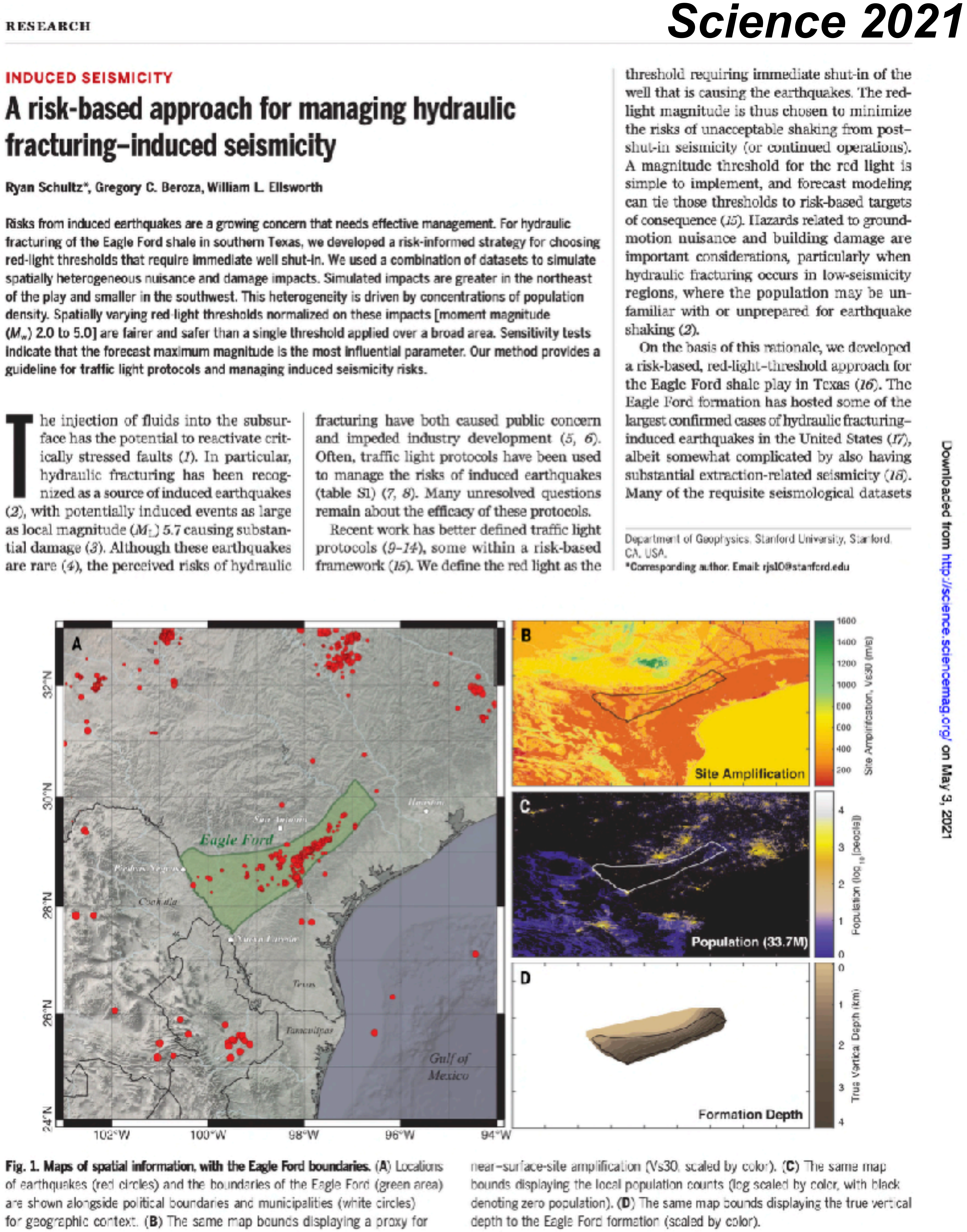
Science 2021



INDUCED SEISMICITY

A risk-based approach for managing hydraulic fracturing–induced seismicity

Ryan Schultz*, Gregory C. Beroza, William L. Ellsworth

Risks from induced earthquakes are a growing concern that needs effective management. For hydraulic fracturing of the Eagle Ford shale in southern Texas, we developed a risk-informed strategy for choosing red-light thresholds that require immediate well shut-in. We used a combination of datasets to simulate spatially heterogeneous nuisance and damage impacts. Simulated impacts are greater in the northeast of the play and smaller in the southwest. This heterogeneity is driven by concentrations of population density. Spatially varying red-light thresholds normalized on these impacts [moment magnitude (M_w) 2.0 to 5.0] are fairer and safer than a single threshold applied over a broad area. Sensitivity tests indicate that the forecast maximum magnitude is the most influential parameter. Our method provides a guideline for traffic light protocols and managing induced seismicity risks.

The injection of fluids into the subsurface has the potential to reactivate critically stressed faults (*1*). In particular, hydraulic fracturing has been recognized as a source of induced earthquakes (*2*), with potentially induced events as large as local magnitude (M_L) 5.7 causing substantial damage (*3*). Although these earthquakes are rare (*4*), the perceived risks of hydraulic fracturing have both caused public concern and impeded industry development (*5*, *6*). Often, traffic light protocols have been used to manage the risks of induced earthquakes (table S1) (*7*, *8*). Many unresolved questions remain about the efficacy of these protocols.

Recent work has better defined traffic light protocols (*9*–*14*), some within a risk-based framework (*15*). We define the red light as the threshold requiring immediate shut-in of the well that is causing the earthquakes. The red-light magnitude is thus chosen to minimize the risks of unacceptable shaking from post–shut-in seismicity (or continued operations). A magnitude threshold for the red light is simple to implement, and forecast modeling can tie those thresholds to risk-based targets of consequence (*15*). Hazards related to ground-motion nuisance and building damage are important considerations, particularly when hydraulic fracturing occurs in low-seismicity regions, where the population may be unfamiliar with or unprepared for earthquake shaking (*2*).

On the basis of this rationale, we developed a risk-based, red-light–threshold approach for the Eagle Ford shale play in Texas (*16*). The Eagle Ford formation has hosted some of the largest confirmed cases of hydraulic fracturing–induced earthquakes in the United States (*17*), albeit somewhat complicated by also having substantial extraction-related seismicity (*18*). Many of the requisite seismological datasets

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Fig. 1. Maps of spatial information, with the Eagle Ford boundaries. (**A**) Locations of earthquakes (red circles) and the boundaries of the Eagle Ford (green area) are shown alongside political boundaries and municipalities (white circles) for geographic context. (**B**) The same map bounds displaying a proxy for near-surface-site amplification (Vs30, scaled by color). (**C**) The same map bounds displaying the local population counts (log scaled by color, with black denoting zero population). (**D**) The same map bounds displaying the true vertical depth to the Eagle Ford formation (scaled by color).

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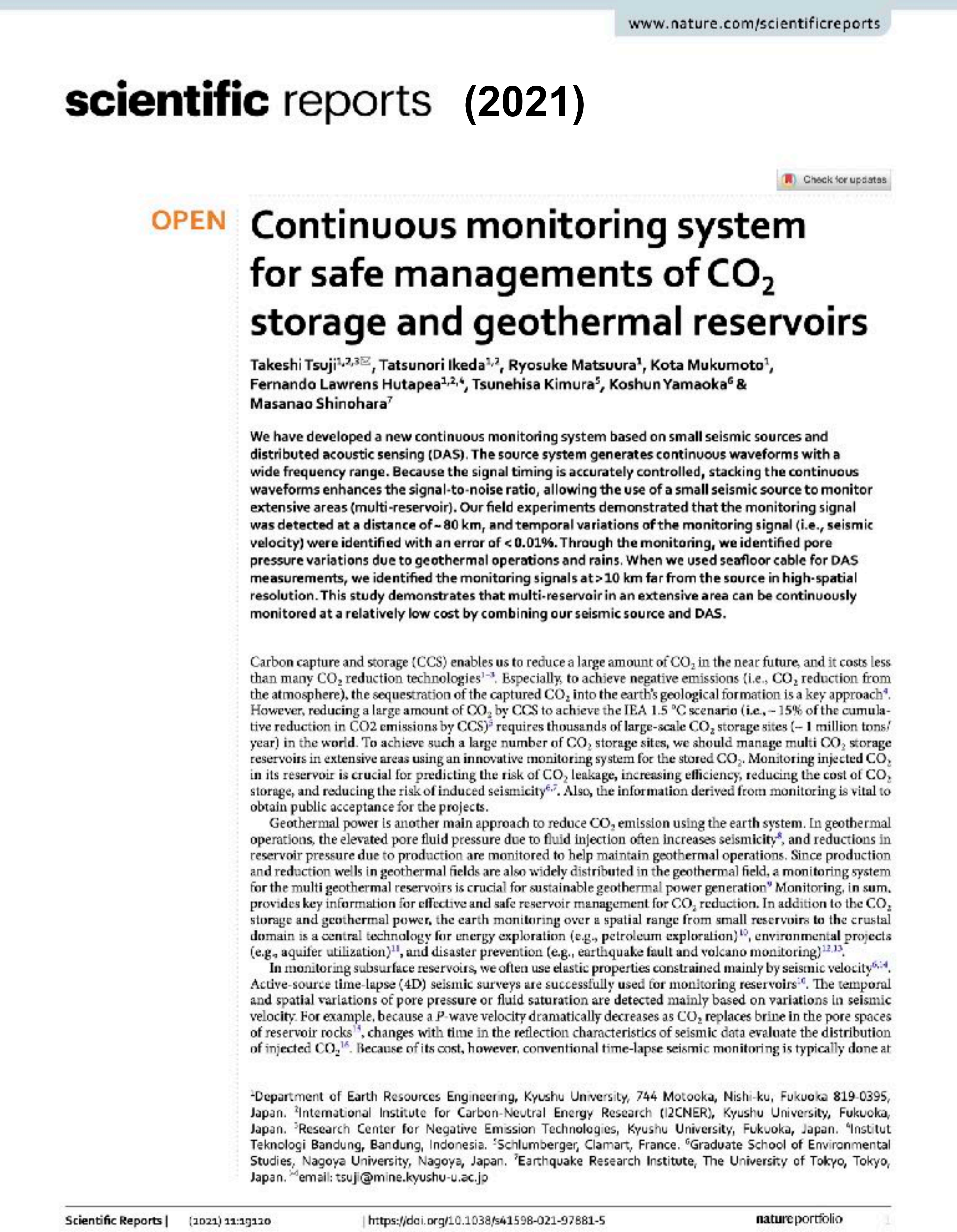
scientific reports (2021)



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OPEN

Continuous monitoring system for safe managements of CO_2 storage and geothermal reservoirs

Takeshi Tsuji[1,2,3]✉, Tatsunori Ikeda[1,2], Ryosuke Matsuura[1], Kota Mukumoto[1], Fernando Lawrens Hutapea[1,2,4], Tsunehisa Kimura[5], Koshun Yamaoka[6] & Masanao Shinohara[7]

We have developed a new continuous monitoring system based on small seismic sources and distributed acoustic sensing (DAS). The source system generates continuous waveforms with a wide frequency range. Because the signal timing is accurately controlled, stacking the continuous waveforms enhances the signal-to-noise ratio, allowing the use of a small seismic source to monitor extensive areas (multi-reservoir). Our field experiments demonstrated that the monitoring signal was detected at a distance of ~ 80 km, and temporal variations of the monitoring signal (i.e., seismic velocity) were identified with an error of < 0.01%. Through the monitoring, we identified pore pressure variations due to geothermal operations and rains. When we used seafloor cable for DAS measurements, we identified the monitoring signals at > 10 km far from the source in high-spatial resolution. This study demonstrates that multi-reservoir in an extensive area can be continuously monitored at a relatively low cost by combining our seismic source and DAS.

Carbon capture and storage (CCS) enables us to reduce a large amount of CO_2 in the near future, and it costs less than many CO_2 reduction technologies[1–3]. Especially, to achieve negative emissions (i.e., CO_2 reduction from the atmosphere), the sequestration of the captured CO_2 into the earth's geological formation is a key approach[4]. However, reducing a large amount of CO_2 by CCS to achieve the IEA 1.5 °C scenario (i.e., ~ 15% of the cumulative reduction in CO2 emissions by CCS)[5] requires thousands of large-scale CO_2 storage sites (~ 1 million tons/year) in the world. To achieve such a large number of CO_2 storage sites, we should manage multi CO_2 storage reservoirs in extensive areas using an innovative monitoring system for the stored CO_2. Monitoring injected CO_2 in its reservoir is crucial for predicting the risk of CO_2 leakage, increasing efficiency, reducing the cost of CO_2 storage, and reducing the risk of induced seismicity[6,7]. Also, the information derived from monitoring is vital to obtain public acceptance for the projects.

Geothermal power is another main approach to reduce CO_2 emission using the earth system. In geothermal operations, the elevated pore fluid pressure due to fluid injection often increases seismicity[8], and reductions in reservoir pressure due to production are monitored to help maintain geothermal operations. Since production and reduction wells in geothermal fields are also widely distributed in the geothermal field, a monitoring system for the multi geothermal reservoirs is crucial for sustainable geothermal power generation[9] Monitoring, in sum, provides key information for effective and safe reservoir management for CO_2 reduction. In addition to the CO_2 storage and geothermal power, the earth monitoring over a spatial range from small reservoirs to the crustal domain is a central technology for energy exploration (e.g., petroleum exploration)[10], environmental projects (e.g., aquifer utilization)[11], and disaster prevention (e.g., earthquake fault and volcano monitoring)[12,13].

In monitoring subsurface reservoirs, we often use elastic properties constrained mainly by seismic velocity[6,14]. Active-source time-lapse (4D) seismic surveys are successfully used for monitoring reservoirs[16]. The temporal and spatial variations of pore pressure or fluid saturation are detected mainly based on variations in seismic velocity. For example, because a *P*-wave velocity dramatically decreases as CO_2 replaces brine in the pore spaces of reservoir rocks[15], changes with time in the reflection characteristics of seismic data evaluate the distribution of injected CO_2[16]. Because of its cost, however, conventional time-lapse seismic monitoring is typically done at

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Seismological Research Letters 2022

A Project Lifetime Approach to the Management of Induced Seismicity Risk at Geologic Carbon Storage Sites

Dennise C. Templeton*[1], Martin Schoenball[2,3], Corinne E. Layland-Bachmann[2], William Foxall[2], Yves Guglielmi[2], Kayla A. Kroll[1], Jeffrey A. Burghardt[4], Robert Dilmore[5], and Joshua A. White[1]

Abstract

The geologic storage of carbon dioxide (CO_2) is one method that can help reduce atmospheric CO_2 by sequestering it into the subsurface. Large-scale deployment of geologic carbon storage, however, may be accompanied by induced seismicity. We present a project lifetime approach to address the induced seismicity risk at these geologic storage sites. This approach encompasses both technical and nontechnical stakeholder issues related to induced seismicity and spans the time period from the initial consideration phase to postclosure. These recommendations are envisioned to serve as general guidelines, setting expectations for operators, regulators, and the public. They contain a set of seven actionable focus areas, the purpose of which are to deal proactively with induced seismicity issues. Although each geologic carbon storage site will be unique and will require a custom approach, these general best practice recommendations can be used as a starting point to any site-specific plan for how to systematically evaluate, communicate about, and mitigate induced seismicity at a particular reservoir.

Cite this article as Templeton, D. C., M. Schoenball, C. E. Layland-Bachmann, W. Foxall, Y. Guglielmi, K. A. Kroll, J. A. Burghardt, R. Dilmore, and J. A. White (2022). A Project Lifetime Approach to the Management of Induced Seismicity Risk at Geologic Carbon Storage Sites, *Seismol. Res. Lett.* **XX,** 1–10, doi: 10.1785/0220210284.

Introduction

Geologic carbon storage (GCS) is one technology that can reduce CO_2greenhouse gas emissions to the atmosphere by utilizing favorable hydrogeologic conditions to sequester CO_2 into the subsurface. However, increased subsurface fluid injection activity has led to an uptick of seismicity at some fluid injection sites, including near wastewater disposal sites, hydraulic fracturing sites, and engineered geothermal systems (EGS; Ellsworth, 2013; Keranen and Weingarten, 2018; Templeton *et al.*, 2020). This induced seismicity has raised concerns about the scalability of GCS considering the seismic hazard and risk associated with far-reaching subsurface pressurization and adjacent basement rocks (Zoback and Gorelick, 2012; White and Foxall, 2016).

Few commercial scale GCS sites exist that can be used as prototypes to study the induced seismic response. Two well-studied examples are the Illinois basin–Decatur (IDBP) project and the associated Illinois Industrial Carbon Capture and Sequestration Sources (IL-ICCS) project. To date, combined they have injected 2.8 million tons of CO_2 into the Mt. Simon saline sandstone reservoir and have detected nearly 20,000 seismic events with magnitudes between −2.1 and 1.2, although none have been felt at the surface (Williams-Stroud *et al.*, 2020). The IL-ICCS project moved the injection to a shallower zone in which a higher injection rate could be sustained with substantially lower seismic activity.

Although those two projects have been a success story in terms of induced seismicity management, a systematic strategy for dealing with induced seismicity is needed to be able to scale up, both in number and in injection volumes. This strategy should additionally be able to incorporate the fact that several GCS sites may be operating simultaneously within the same basin for extended periods of time, thus potentially posing a hazard to a much larger region. Zhou *et al.* (2010) modeled a scenario for 20 injection sites in the Illinois basin spaced approximately 30 km apart, each injecting about 5 Mt/yr over 50 yr. The modeled pressure behavior is observed to have an early stage in which individual injection well pressurizations do not interfere. This is followed by an intermediate phase in which transient pressure interference is observed between the injection sites and is followed by a final phase in which a continuous pressure buildup is driven by the combined behavior of all injection sites within the basin.

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EXCELENCIA SEVERO OCHOA

ICREA

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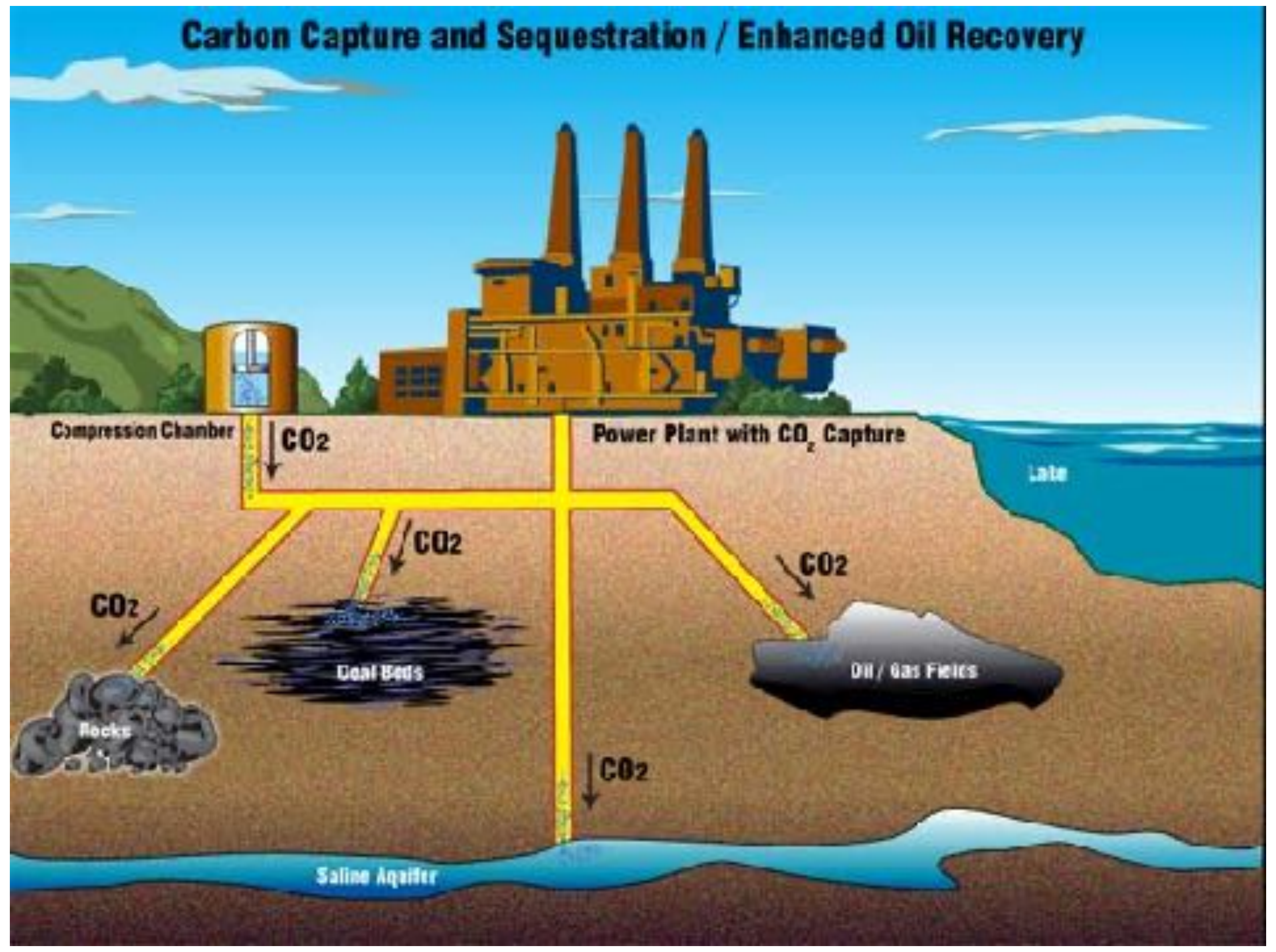
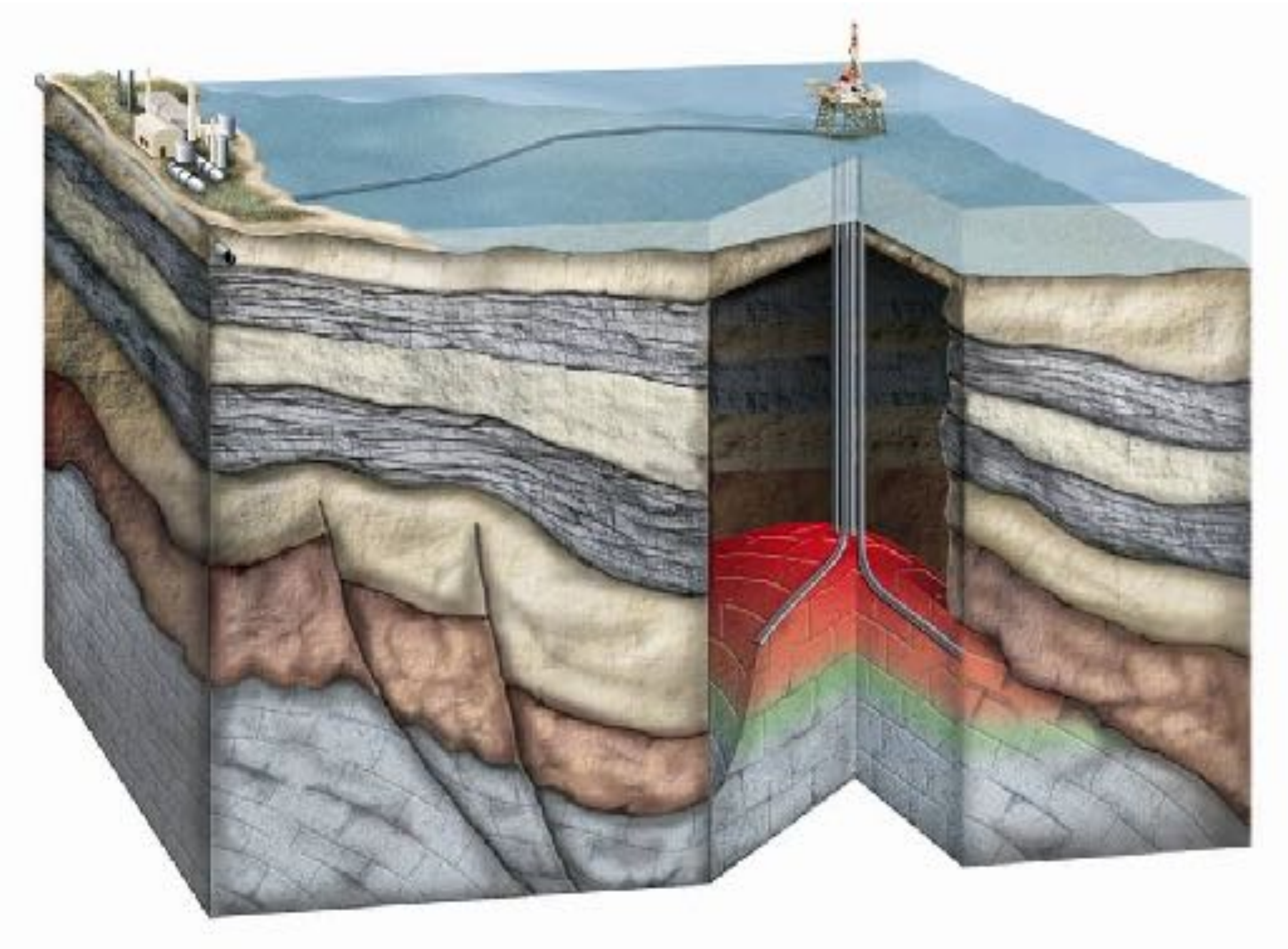
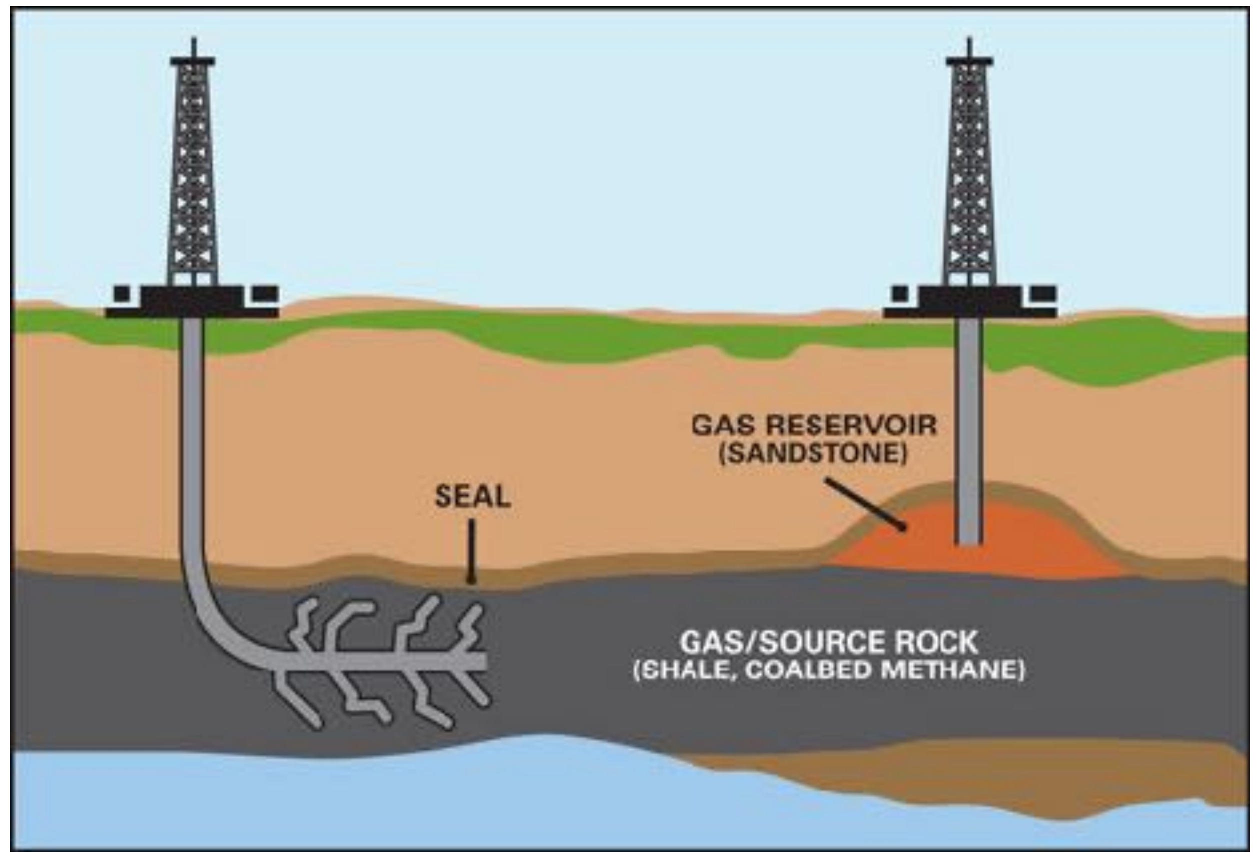
Monitorizacion Sísmica: OBLIGATORIA en proyectos de inyección o extracción de fluidos del subsuelo



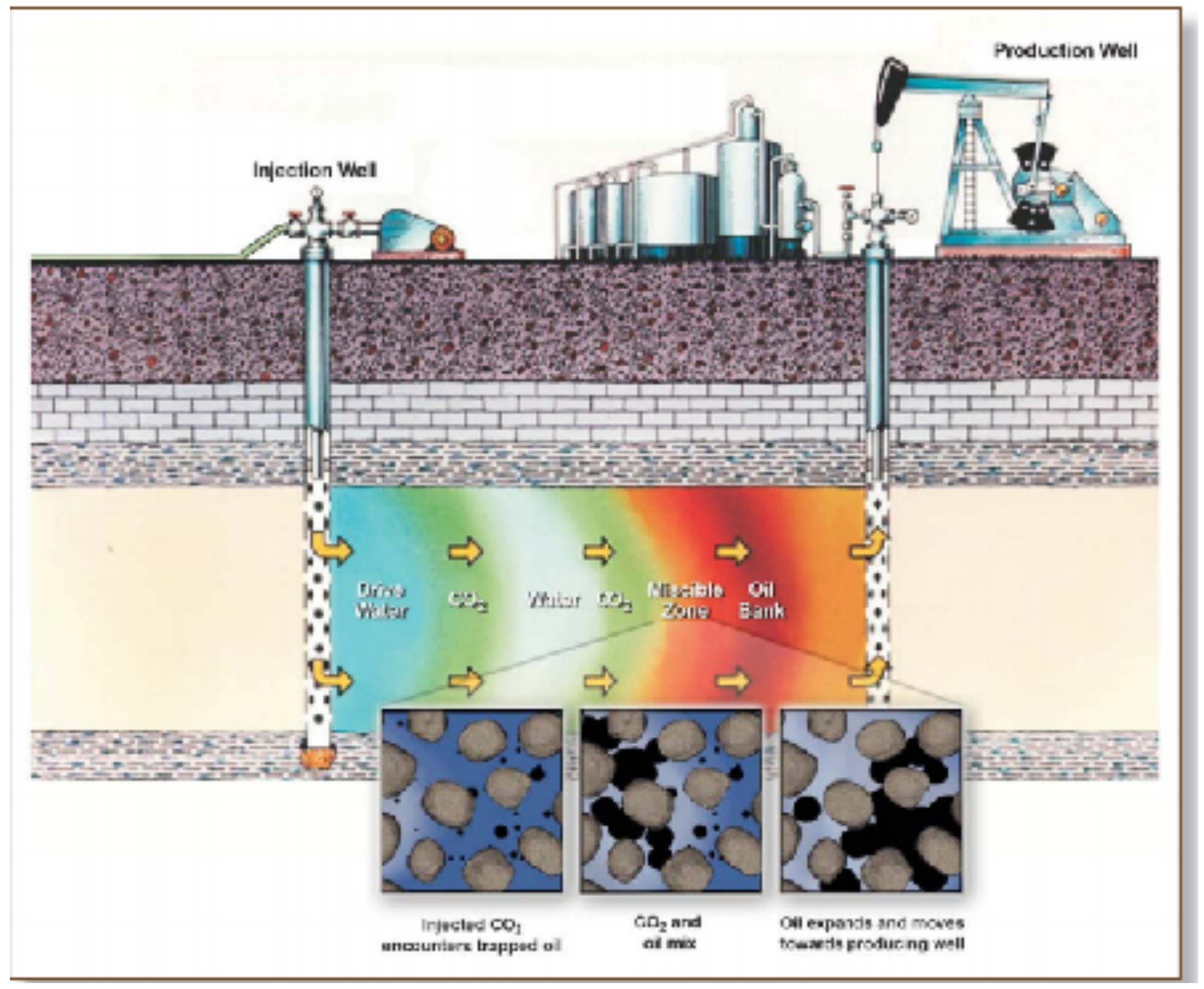
CO_2 injection



Underground gas or hydrogen storage



Fracking



Enhanced oil recovery

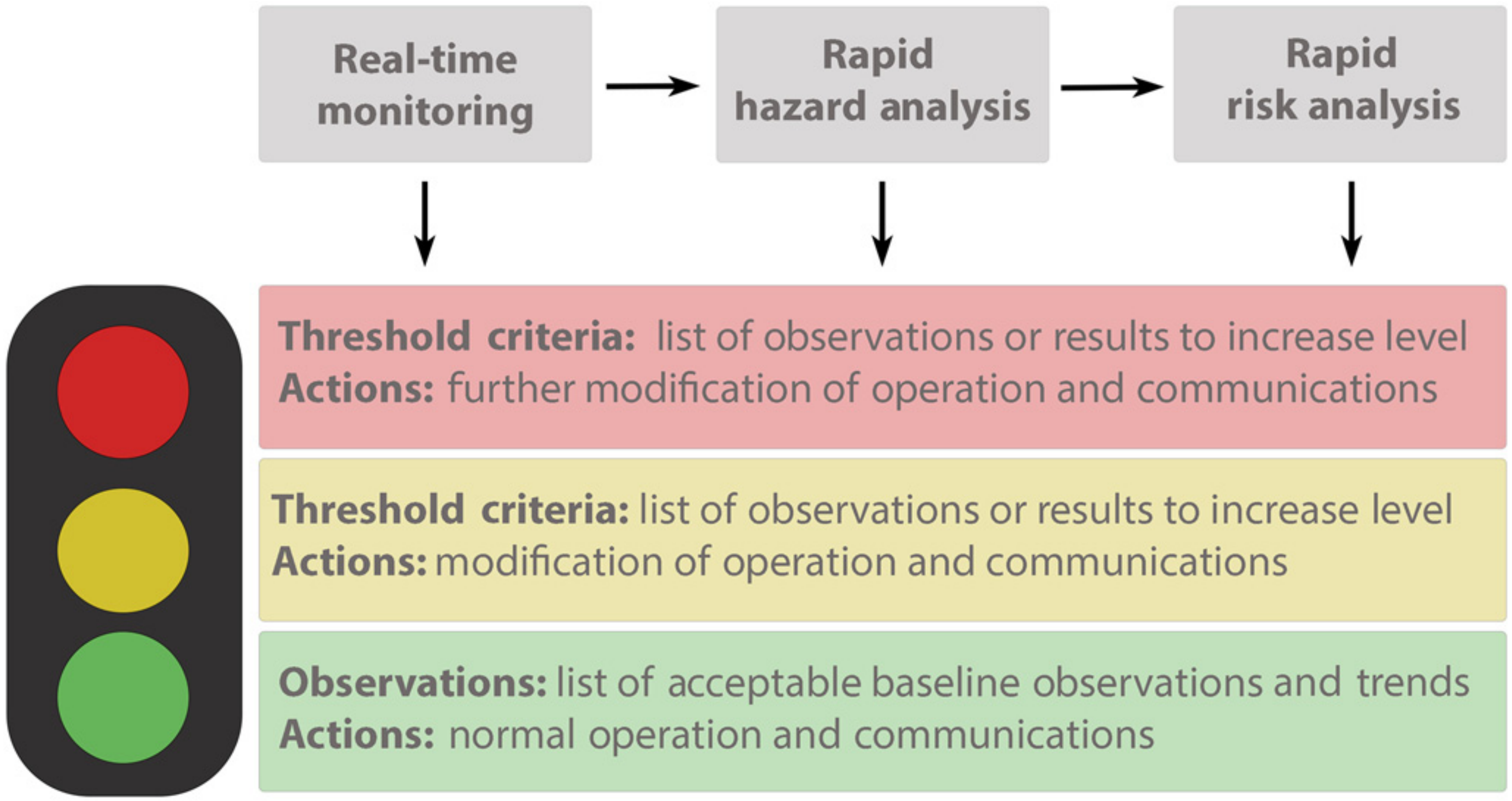
Recomendaciones (Regulatorias?)

- **<u>Almacenes en zonas de bajo riesgo</u>: Mar afuera, si es posible, para minimizar impacto sismicidad inducida.**

- **Estudio <u>Sismicidad Linea de Base</u>: Revisión de los registros originales (NO usar directamente catalogo existente).**

- **<u>Monitorización</u> del almacen y alrededores con red sismológica**
  - **Empezar años antes de comenzar el almacenamiento.**
  - **Definir un Sistema de alerta de semáforos.**
  - **Preparar un Plan de Gestión del Riesgo (respuesta ante la actividad sísmica).**
  - **Monitorizar el movimiento de la pluma del fluido inyectado (integridad almacén).**

Sistema de semáforos



Real-time monitoring → Rapid hazard analysis → Rapid risk analysis

Threshold criteria: list of observations or results to increase level
Actions: further modification of operation and communications

Threshold criteria: list of observations or results to increase level
Actions: modification of operation and communications

Observations: list of acceptable baseline observations and trends
Actions: normal operation and communications

Figure 1. Example adaptive traffic light system. Real time seismic, hydraulic, and operational monitoring can either directly increase the response level or indirectly help inform rapid hazard and risk analyses that may prompt a change in response level due to updated results. The color version of this figure is available only in the electronic edition.

Seismological Research Letters 2022

Estudios de Sismicidad Local:

↓

Definir Sísmicidad de base

Elementos de la monitorización sísmica

- **Diseño de la red (número de sensores, estudio de la geometría)**
- **Sistema de adquisición en tiempo real para la detección y localización**
- **Determinación de las magnitudes y mecanismos focales**
- **Sistema de alerta (semáforos)**
- **Plan de gestión del riesgo (respuesta ante la actividad sísmica)**
- **Seguimiento del movimiento de la pluma inyectada (integridad almacén)**

Monitorizacion submarina

Sismómetros de fondo marino

Tecnología de Sensado Acústico Distribuido (DAS)

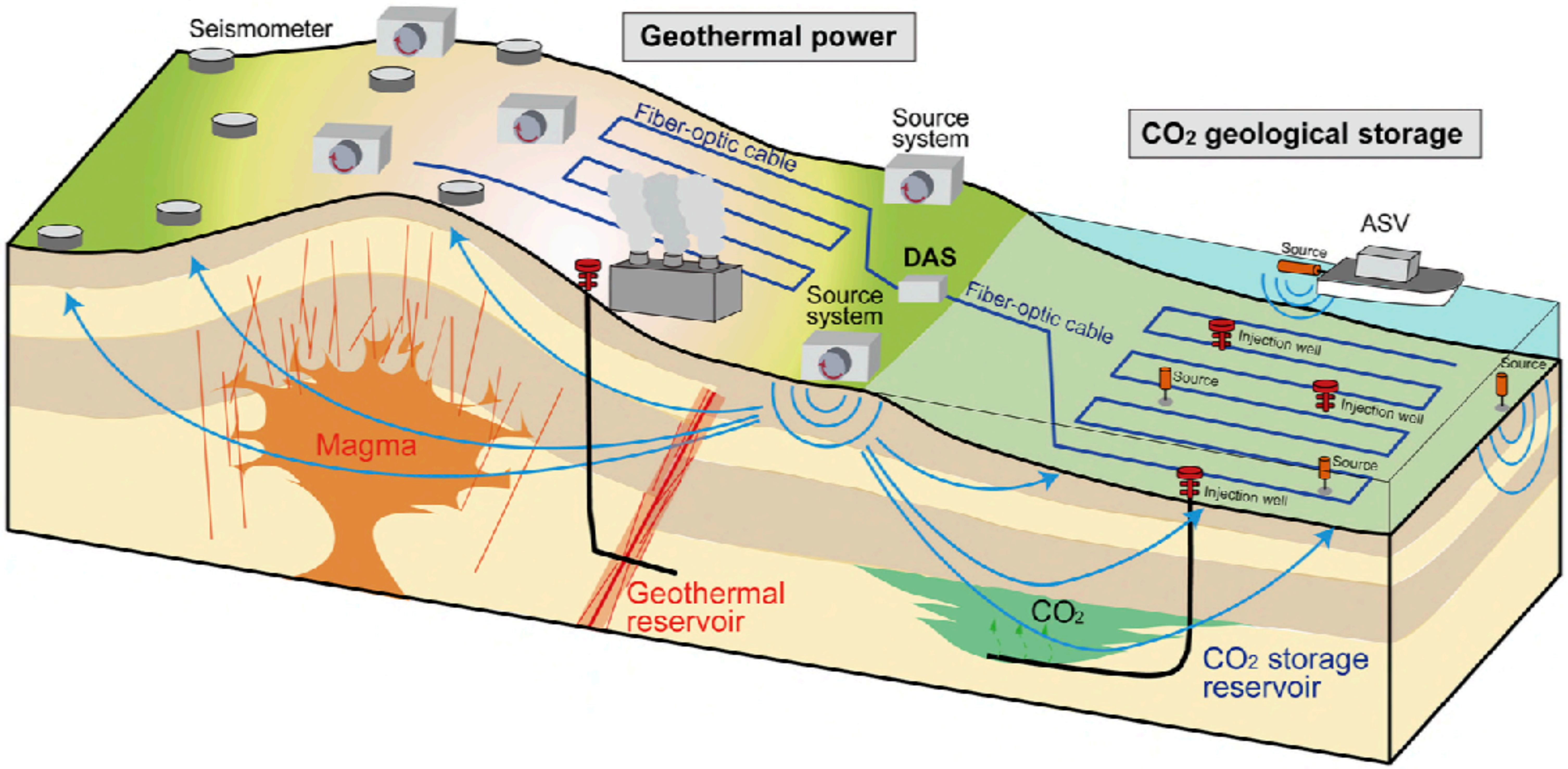


Figure 10. Schematic image of continuous monitoring systems and seismometer networks, including a D
array. We manage the multi-reservoir using our continuous monitoring system.

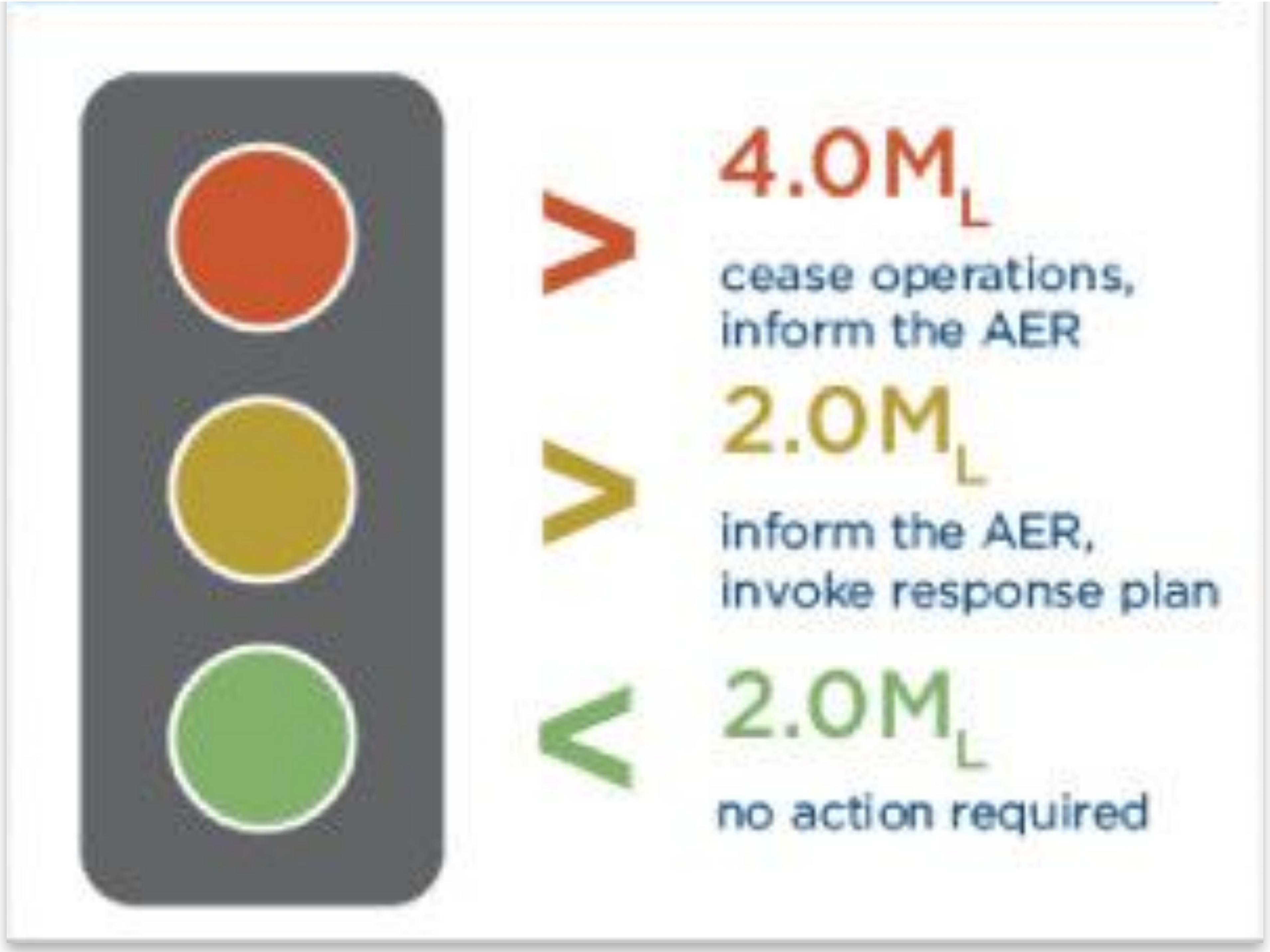
Tsuji et al., (Sci. Rep. 2021)

Sistemas de Semaforos

Sistema de semáforos en uso

Magnitude-based traffic light system

Canada

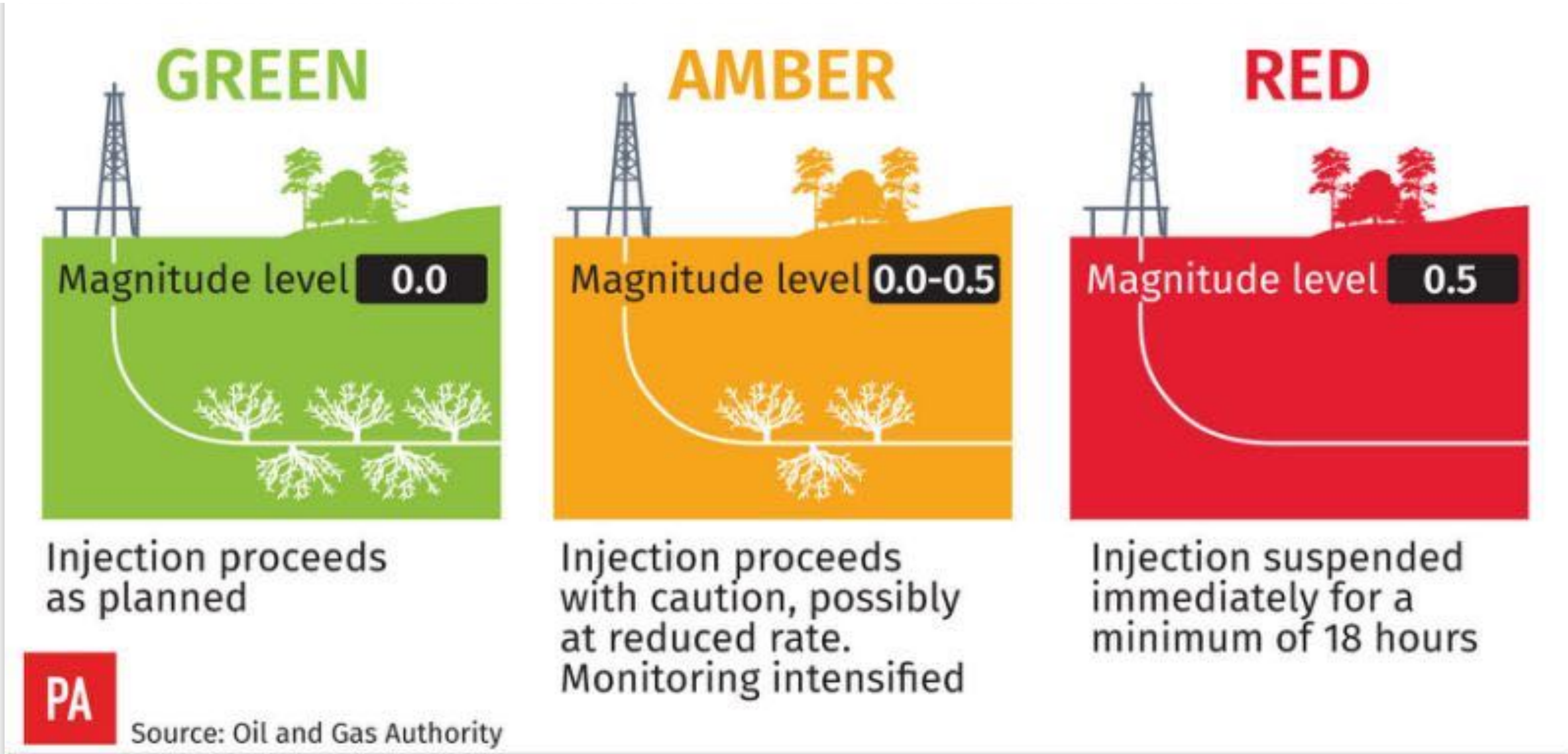


$> 4.0M_L$
cease operations, inform the AER

$> 2.0M_L$
inform the AER, invoke response plan

$< 2.0M_L$
no action required

United Kingdom



GREEN
Magnitude level 0.0
Injection proceeds as planned

AMBER
Magnitude level 0.0-0.5
Injection proceeds with caution, possibly at reduced rate. Monitoring intensified

RED
Magnitude level 0.5
Injection suspended immediately for a minimum of 18 hours

PA
Source: Oil and Gas Authority

Conclusiones - Sismicidad Inducida

- **Comparativamente riesgo controlable:** Profundidad de injección de CO_2 en rocas poco consolidadas resultando en sismicidad de pequeña M.

- **Regulaciones** posiblemente comunes a todas las actividades de almacenamiento

- **Elección y monitorización del almacén**: Estudio Sismicidad de Base, Monitorización tiempo real, Sistema de Semaforos, Plan de Gestion de Riesgo.

- ***Nuevas Tecnologías** de monitorización: bajo impacto ambiental, coste moderado, alta resolución.*

END