HiQuake: The Human-Induced Earthquake Database

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ABSTRACT

HiQuake—The Human-Induced Earthquake Database is the most complete database of anthropogenic projects proposed, on scientific grounds, to have induced earthquake sequences. It is freely available to download from the website given in Data and Resources. At the time this article was written, *HiQuake* contained ~730 anthropogenic projects proposed to have induced earthquakes, as well as associated project-related and seismic data. The most commonly reported anthropogenic activities proposed to have induced earthquakes are mining and water reservoir impoundment. In recent years, the number of earthquake sequences proposed to have been induced by fluid-injection activities has grown. The most commonly reported maximum observed magnitude in an induced earthquake sequence is $3 \le M_{MAX} < 4$. The largest earthquake in *HiQuake* proposed to have been induced had a magnitude of M_w 7.9 and occurred in China. Such large earthquakes release mostly stress of natural tectonic origin, but are conceivably triggered by small anthropogenic stress changes. The data in *HiQuake* are of variable quality because they are drawn from publications that span almost a century. We estimate underreporting to be ~30% for $M \sim 4$ events, ~60% for $M \sim 3$ events, and ~90% for $M \sim 2$ events. The degree of certitude that the given earthquake sequences were anthropogenically induced is variable. *HiQuake* includes all earthquake sequences proposed on scientific grounds to have been human induced without regard to the strength of the case made. *HiQuake* is offered freely as a resource to interested parties, and judging the reliability of any particular case is the responsibility of the database user. *HiQuake* will be routinely updated to correct errors, update existing entries, and add new entries. It has the potential to help improve our understanding of induced earthquakes and to manage their impact on society.

INTRODUCTION

Induced earthquakes can pose a direct threat to infrastructure and human life, and fear of them can impact project viability. Understanding and managing them is thus of economic and social importance. Estimating the maximum possible magnitude earthquake that a project may induce (e.g., McGarr *et al.*, 2002; McGarr, 2014; van der Elst *et al.*, 2016) is of particular interest, because this parameter is important for hazard assessment. In the last few years, the study of induced earthquakes has intensified, primarily because of the coincident increase in seismic rates and waste-fluid disposal activities in the United States, but also due to the expanding use of hydraulic fracturing for shale gas and oil recovery (Ellsworth, 2013). Many cases of induced earthquakes have been studied in detail and documented. The first documented case of induced seismicity related to underground fluid injection occurred at the Rocky Mountain Arsenal, Denver, in the 1960s (Evans, 1966). These cases provide a large body of data that gives context to modern induced earthquake sequences and can help improve understanding of the phenomenon.

In 2016, Nederlandse Aardolie Maatschappij BV (NAM), a Dutch oil and gas exploration and production company, funded a team of researchers from Durham and Newcastle Universities, United Kingdom, to conduct a full review of induced earthquakes. This review extended a study by Davies *et al.* (2013) in which 198 cases of induced earthquake sequences were documented where the largest event had a magnitude of $M \ge 1.0$. Until the present project, this was the best-known publically available database of induced earthquakes, although other compilations focusing on specific anthropogenic activities also exist (e.g., Gupta, 2002; Li *et al.*, 2007; Suckale, 2009; Evans *et al.*, 2012). Extending the database by Davies *et al.* (2013) became a component of a project led by NAM that aimed to estimate the maximum possible magnitude earthquake that might be induced in the Groningen gas field, The Netherlands, which NAM operates (NAM, 2016). Induced earthquakes probably began to occur due to gas production in the late 1970s, with the first officially registered induced earthquake in 1986 (van der Voort and Vanclay, 2015). The Groningen gas field is one of the largest gas fields in the world and is therefore of significant economic importance. Consequently, gas production continues but to assist with mitigation measures for induced earthquakes, NAM has made financial commitments to researching induced seismicity.

The resulting database of the full review, The Human-Induced Earthquake Database (*HiQuake*), was formally released on 26 January 2017 via the website given in Data and Resources. It has subsequently been maintained and updated,

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and the plan is to continue this work for the foreseeable future. *HiQuake* is currently the largest and most up-to-date freely available database of projects proposed to have induced earthquake sequences. This article formally documents *HiQuake*, describes how it was developed (including policy decisions that had to be made), provides an overview of its contents, and reports initial observations. A more extensive review of induced earthquakes based on the knowledge gained while developing *HiQuake*, and including specific case studies, is given by Foulger *et al.* (2017).

DATABASE CONTENTS AND AVAILABILITY

HiQuake was compiled from peer-reviewed published literature, industry reports, government reports, academic presentations, media articles, and personal communications. A thorough search for projects proposed to have induced earthquakes was conducted using a variety of methods, including searching online databases for keywords, checking all relevant papers in the reference lists of known papers, searching the proceedings of major conferences, searching for reports published online, and gathering personal communications. After approximately six person-months of work, we essentially ceased to find any additional historical examples and the database grew primarily by the addition of contemporary cases.

As the database grew, it became clear that the strength of the scientific case for induction varied from extremely strong to extremely weak, with many projects in between. A decision had to be made regarding how strong the case should be for inclusion in the database. Because of the subjectivity of judging the plausibility of individual cases, and the inevitability that opinion among researchers would vary widely, it was decided to include all cases without regard to plausibility. The database thus lists all projects proposed on scientific grounds (not religious or moral) to have induced earthquake sequences. Judgment regarding the strength of the case made for any particular entry is the responsibility of the user.

Each entry in *HiQuake* corresponds to a single project or distinct phase of a project. Some projects have been underway for many years and have probably induced tens of thousands of earthquakes; for example, geothermal operations at The Geysers field, California (Majer and Peterson, 2007). Other projects were completed in a few hours or days and may have induced only a few earthquakes; for example, hydraulic fracturing at Preese Hall, United Kingdom, which was associated with 52 recorded earthquakes (Clarke *et al.*, 2014). Regardless of the total number of earthquakes reported, each project or distinct project phase corresponds to a single entry in *HiQuake*. In some cases, the type of anthropogenic activity proposed to have induced earthquakes is uncertain. For example, in some hydrocarbon reservoirs, fluid extraction and injection have occurred simultaneously for many years. Along with the project name, other data recorded in *HiQuake* include project type, location, maximum observed magnitude earthquake (M_{MAX}), and operational parameters. A full list of database columns is given in Table 1.

Table 1
List of Column Names within The Human-Induced Earthquake Database (*HiQuake*)

Column Contents
Country
Earthquake cause (main class)
Earthquake cause (subclass)
Project name
Latitude
Longitude
Project start date
Project end date
Seismicity or monitoring start date
Seismicity or monitoring end date
Delay time
Number of recorded earthquakes
Maximum observed magnitude (M_{MAX})
Magnitude type
Depth of M_{MAX} (m)
Date of M_{MAX} (yyyy/mm/dd)
Year of M_{MAX}
Distance of M_{MAX} to project (m)
Maximum distance of earthquakes to project (m)
Lithology/resource
Depth of most seismicity (m)
Depth of project (m)
Tectonic setting
Notable previous seismicity
Dam height (m)
Area (km^2)
Maximum injection/extraction rate
Units of injection/extraction rate
Total volume or mass of material injected/extracted
Units of total volume or mass of material injected/extracted
Maximum injection pressure (MPa)
Change in reservoir pressure (MPa)
Stress change (MPa)
Bottom hole temperature (°C)
Notes
Reference(s)

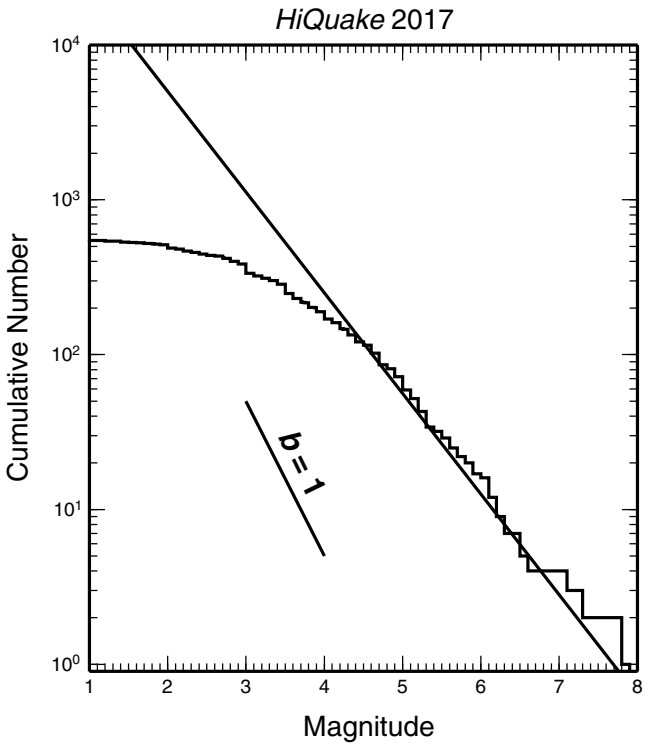
The quality of the data in *HiQuake* varies because the database includes earthquakes that occurred up to ~150 years ago and draws from publications as far back as 1931. The completeness of the record and the accuracy of the data are expected to be poorer for older cases. A variety of magnitude types for M_{MAX} are given in *HiQuake* because seismological practice has changed greatly with time. Magnitude types within the database include M_L (local magnitude), m_b (body-wave magnitude), M_s (surface-wave magnitude), M_D (duration magnitude), and M_w (moment magnitude). Where a magnitude type is not specified in the data source, we use the

Table 2
The Numbers of Each Type of Anthropogenic Activity Proposed to Have Induced Earthquakes (Data from *HiQuake*)

Anthropogenic Activity	Number of Reported Cases	Percentage of *HiQuake* to Nearest Integer (%)
Carbon capture and storage (CCS)	2	0
Construction	2	0
Conventional oil and gas	107	15
Deep penetrating bombs	4	1
Hydraulic fracturing for shale gas or oil	29	4
Geothermal	57	8
Groundwater extraction	5	1
Mining	271	37
Nuclear explosions	22	3
Research experiments	14	2
Unspecified oil and gas extraction; waste-fluid disposal	12	2
Waste-fluid disposal	36	5
Water reservoir impoundment	167	23
Total	728	

notation M. If M_w is provided, we preferentially cite this. Because magnitudes measured using different scales are not necessarily equivalent, this factor should be borne in mind when testing for correlations between earthquake magnitude and other parameters. Rendering all the magnitudes to a common scale is a subject for future work.

HiQuake is freely available to all stakeholders including industrialists, engineers, scientists, governments, and the general public. It provides basic context that may help stakeholders understand the significance of induced earthquakes in context with other industrial costs, hazards, and benefits. It can also be used for research; for example, to study correlations between seismicity and operational parameters. This may assist in the design of hazard assessment strategies for industrial projects. *HiQuake* is available in Microsoft Excel spreadsheet format at the website given in Data and Resources. This format was chosen because of the wide variety of numerical and text data within *HiQuake* and because it is a format widely accessible to both scientists and nonscientists. Scientific users may need to reformat the database for particular uses. Database updates will be made routinely to add new information and correct errors. To facilitate this, the authors would be grateful for any feedback from users, which may be submitted via the web form given in Data and Resources or by contacting the authors directly.

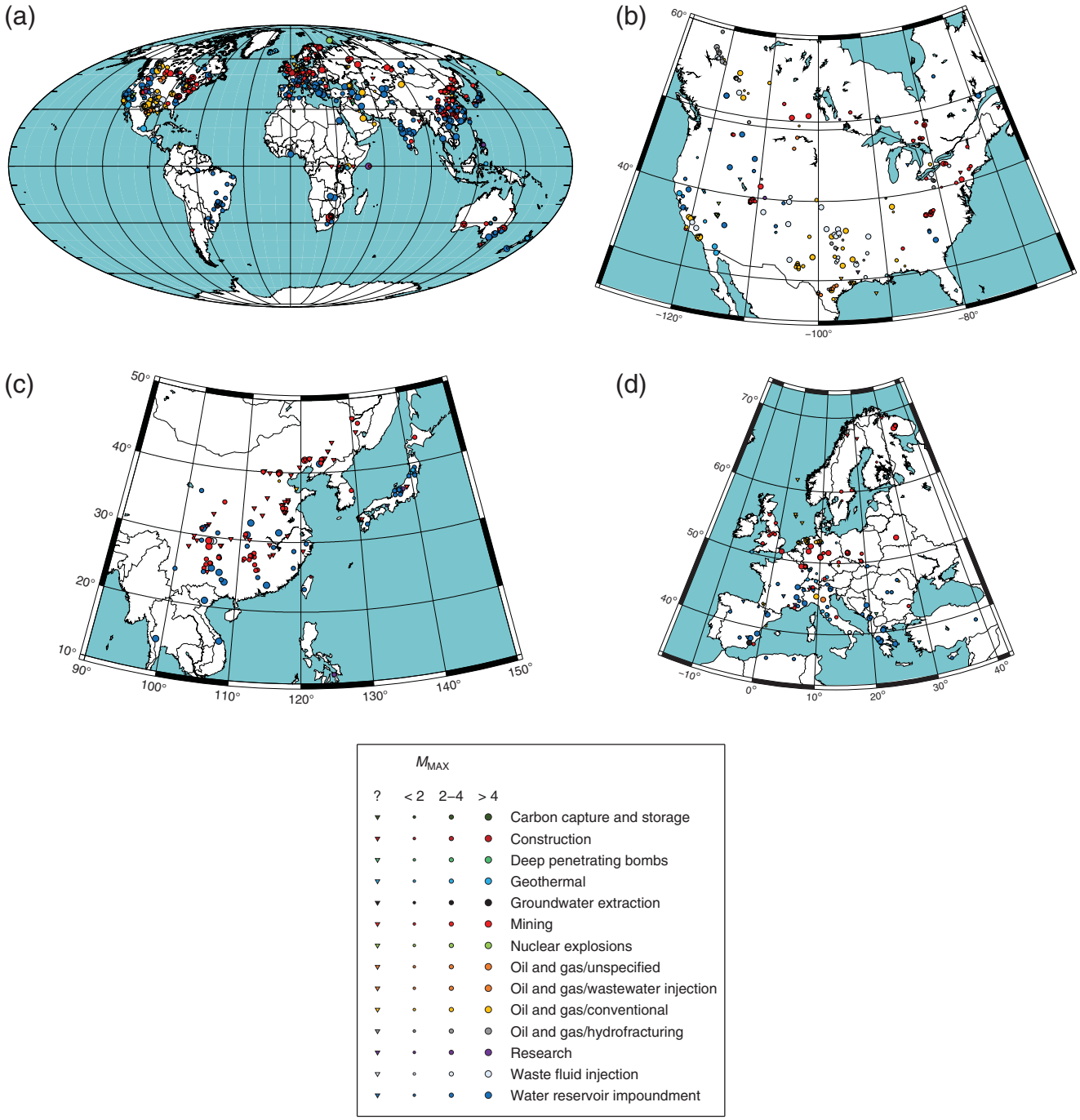


▲ **Figure 1.** Gutenberg–Richter magnitude–frequency plot of the cumulative distribution of M_{MAX} values within The Human-Induced Earthquake Database (*HiQuake*). The stair-step function gives the number of projects for which the largest earthquake has a magnitude exceeding the value given on the abscissa. The straight line has a *b*-value (negative slope) of 0.65, determined from analysis of projects with $M_{MAX} \geq 5$. A reference line with $b = 1$ is also shown.

INITIAL OBSERVATIONS

At the time this article was written, *HiQuake* contained ~730 anthropogenic projects or project phases proposed to have induced earthquakes (Table 2). The project types that contribute the most cases to *HiQuake* are mining (37%) and the impoundment of water behind dams (23%). Injection activities such as hydraulic fracturing for shale gas or oil, waste-fluid disposal, geothermal reinjection, and secondary recovery for hydrocarbons, account for ~10%–15% of cases. Less well-known proposed seismogenic processes include the construction of skyscrapers, quarrying, groundwater extraction, and nuclear bomb testing (seismicity following the explosion event).

In some cases, there is ambiguity regarding the causative process because multiple seismogenic activities may be underway simultaneously; for example, fluid injection and extraction. In addition, there is clearly underreporting. This may result from induced earthquakes going unrecognized or from lack of motivation to report when the induced seismicity is inconsequential to communities or industrial activity. Examination of the fractal distribution of M_{MAX} earthquakes via a Gutenberg–Richter plot shows linearity at the high-magnitude end only for earthquakes $M \geq 5$, which yield a *b*-value of ~0.65 ± 0.15 (95% confidence

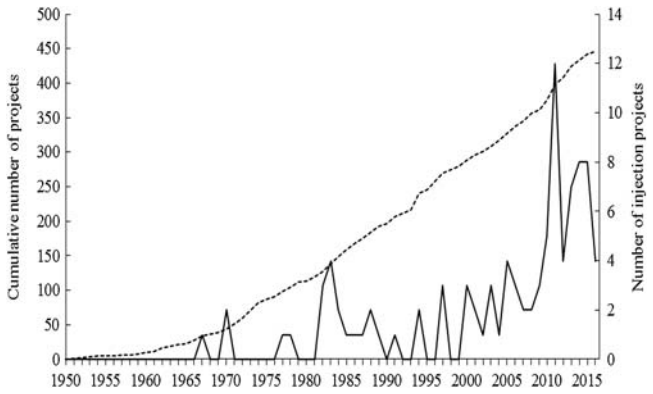


▲ **Figure 2.** Locations of projects proposed to have induced seismicity; (a) World map, (b) North America, (c) Eastern Asia, and (d) Europe. Data from *HiQuake*.

value) (Fig. 1). Extrapolation of the *b*-slope suggests that underreporting is ~30% for $M \sim 4$ events, ~60% for $M \sim 3$ events, and ~90% for $M \sim 2$ events.

The earliest entry in *HiQuake*, from 1868, is coal mining near Maitland, Australia (Klose, 2007a,b). Seismogenic projects are reported from ~70 countries (Fig. 2). The largest contributing countries at the time of writing are the United States (182 cases; Fig. 2b) and China (148 cases; Fig. 2c). This does not necessarily mean these countries host more seismogenic projects; it could be that reporting is more complete. Some anthropogenic activities that are proposed to induce earthquakes, such as water reservoir impoundment and mining, are more globally diffuse than others. The fastest-growing anthropogenic activity proposed to induce earthquakes may be fluid injection (Fig. 3) as exemplified by the recent remarkable increase in induced seismicity in Oklahoma (Keranen *et al.*, 2014).

The most commonly reported M_{MAX} in an induced earthquake sequence is $3 \le M_{MAX} < 4$ (Fig. 4). The largest earth-

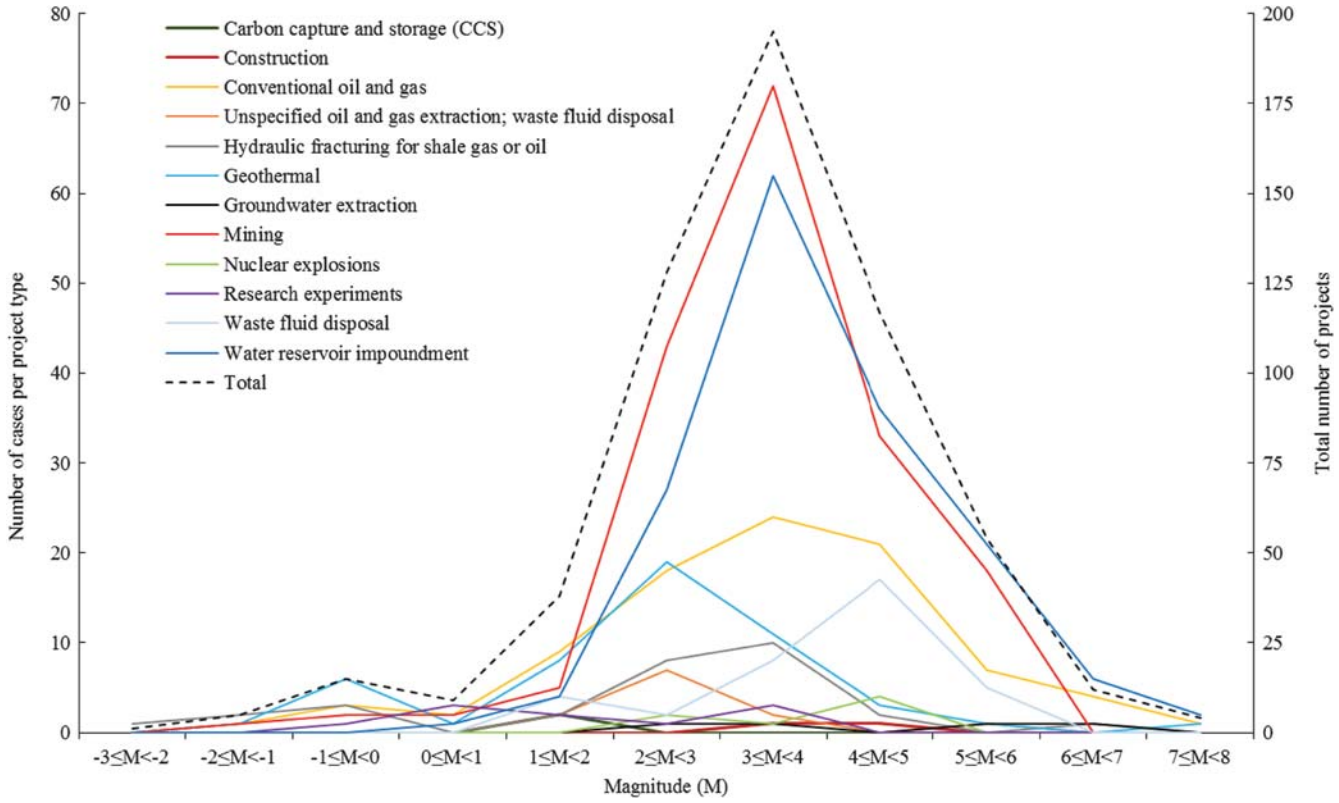


▲ **Figure 3.** Number of projects with reported M_{MAX} earthquakes and year of M_{MAX} since 1950. The dashed line is the cumulative number of all anthropogenic projects and the solid line is the annual number of injection projects. Data from *HiQuake*.

quake reported to date to be induced by fluid injection is M_w 5.8 (the 2016 Pawnee, Oklahoma, earthquake; Yeck *et al.*, 2017), by water reservoir impoundment M_w 7.9 (the 2008 Wenchuan, China, earthquake; Ge *et al.*, 2009), by hydrocarbon extraction M 7.3 (the 1976 Gazli, Uzbekistan, earthquake; Mirzoev *et al.*, 2009), and by groundwater extraction M_w 7.8 (the 2015 Gorkha, Nepal, earthquake; Kundu *et al.*, 2015). A large majority of the stress released by such large earthquakes was without doubt of natural origin and the question of whether or not the event was induced relates to the initial trigger that caused fault slip to start. Large earthquakes commonly comprise a sequence of subevents, each of which is triggered by the previous subevent, so large earthquakes may result from the induction of a much smaller initial event. As mentioned above, we did not judge the strength of cases made and include in *HiQuake* all those for which a scientific case has been presented.

SUMMARY

Durham and Newcastle Universities, under contract with NAM, have constructed the most complete database of human-induced earthquakes (*HiQuake*) currently available. It may be downloaded as a Microsoft Excel spreadsheet (see Data and Resources). At the time the article was written, *HiQuake* listed ~730 anthropogenic projects or project phases proposed to have induced earthquake sequences, along with a suite of metadata accompanying each case. The most commonly reported seismogenic project types are mining and water reservoir impoundment. In recent years, the number of earthquake sequences proposed to have been induced by fluid-injection activities has grown. Reported maximum observed magnitudes are most commonly $3 \le M_{MAX} < 4$, but this range varies depending on project type. The largest earthquake proposed to have been induced to date is the M_w 7.9 Wenchuan earthquake, China. Extremely large earthquakes like this may be initially triggered by a small stress change brought about by anthropogenic activities, but most of the stress released is of natural tectonic origin. *HiQuake* is inhomogeneous because data are drawn from pub-



▲ **Figure 4.** Number of cases versus M_{MAX} for projects in which M_{MAX} is provided. Data from *HiQuake*.

lications spanning almost a century, and the observational detail given and seismological practice have varied during this long time span. Underreporting is a problem and we estimate that it is ~30% for $M \sim 4$ events, ~60% for $M \sim 3$ events, and ~90% for $M \sim 2$ events. The degree of certitude that given earthquake sequences were anthropogenically induced is also variable. *HiQuake* includes all earthquake sequences for which a scientific case has been made for human induction, and judging the reliability of each case is the responsibility of the database user. The database will be updated routinely to correct errors, revise existing entries. and add new entries. *HiQuake* is freely available to all and may be of interest to industrialists, engineers, scientists, governments, and the general public. It may contribute to increasing understanding of the spatial and temporal occurrence of induced earthquakes, their causes and relationships to operational parameters, and thus contribute to increasing industrial safety.

DATA AND RESOURCES

The Human-Induced Earthquake Database (*HiQuake*) is an open-access database available at www.inducedearthquakes.org (last accessed July 2017). At the time this article was written, the most recent update to the database occurred on 25 July 2017. For any feedback, users can submit via the web form www.inducedearthquakes.org/contribute (last accessed July 2017) or by contacting the authors directly.

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