A unified earthquake catalogue for the North Sea to de-risk European CCS operations

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Abstract

Carbon capture and storage (CCS) technology is essential to European decarbonisation efforts, and several offshore CO_2 storage projects are being developed in the North Sea. Understanding the geomechanical response to CO_2 injection is key to both the pre-characterisation and operation of a storage reservoir. A thorough assessment of seismicity gives critical insights into the stress field and faulting around reservoirs, both key controls on the geomechanical response to injection. Seismicity also illuminates potential hydraulic pathways for leakage, be it directly by revealing the extent of faults, or indirectly through fractures imaged by measurements of seismic anisotropy. High quality seismicity data is critical to underpin all of these methods of analysis. This paper presents the most complete catalogue of seismicity in the North Sea to date. The combined data are enabling revised assessments of seismic hazard and leakage risk in the North Sea, as well as a better understanding of faulting and stress. This study shows the value of unifying disparate seismicity data, allowing for more accurate seismological analyses. These lay the foundation for better management of risks for not only geologic CO_2 storage, but other offshore industries and infrastructure.

Introduction

Currently, a number of CO_2 storage projects are being developed in the offshore North Sea region to facilitate European emission-reduction efforts (Figure 1). Despite seismic hazard in the North Sea being comparatively low, it is still critical to assess the rate and size of local earthquakes. In addition, offshore wind projects are prevalent, being expanded to further decarbonise energy systems in Europe. Seismic hazard is a key environmental risk factor for both these industries, and high quality data must be used to accurately characterise and quantify the size of that risk.

High quality seismicity data can highlight the location of faults and other pre-existing structures (e.g., dominant fracture trends) near prospective storage sites, some of which could act as hydraulic conduits for CO_2 migration. Further, faults can impact in situ stresses in and around potential reservoirs, and measuring the propagation of seismic waves generated by earthquakes can act as stress indicators. Understanding the distribution of in situ stress is key to the safe and effective drilling of wells as well as injection of CO_2. Measurements of stress can be found from borehole assessments, but also from seismicity: it can be inverted from earthquake faulting styles, inferred from earthquake stress drops, or measured from seismic anisotropy (e.g., Teanby et al., 2004). High quality earthquake data is required to conduct these analyses. Combining earthquake observations from as many sources as possible leads to improvements in quality. It can thus provide a more robust, quantified, and complete assessment of seismic hazard, as well as the regional state of stress, the understanding of which is vital to securely inject CO_2.

The risk of injection-induced seismicity is also present for CO_2 storage operations. The injection of fluids into the subsurface has been clearly associated with seismicity in a number of geologic and industrial settings (e.g., Keranen & Weingarten, 2018), and the occurrence of microseismicity has been linked to the injection of CO_2 (Cheng et al., 2023) and gas storage (Cesca et al., 2014). Oil and gas exploitation in the North Sea was also associated with several earthquakes typically thought to be triggered primarily by depletion-induced stress changes (Zoback and Zinke 2002; Teanby et al., 2004; Jones et al., 2010). Several mechanisms were invoked for the triggering of faults by injection or depletion, along with several geological controls on the severity or prevalence of induced seismicity (e.g., Kettlety & Verdon, 2021). Seismological investigations provide both direct and indirect observations of many of these controls, and thus seismological data is key to the assessment of induced seismicity risk for CO_2 storage sites (Verdon & Stork, 2016; White & Foxall, 2016).

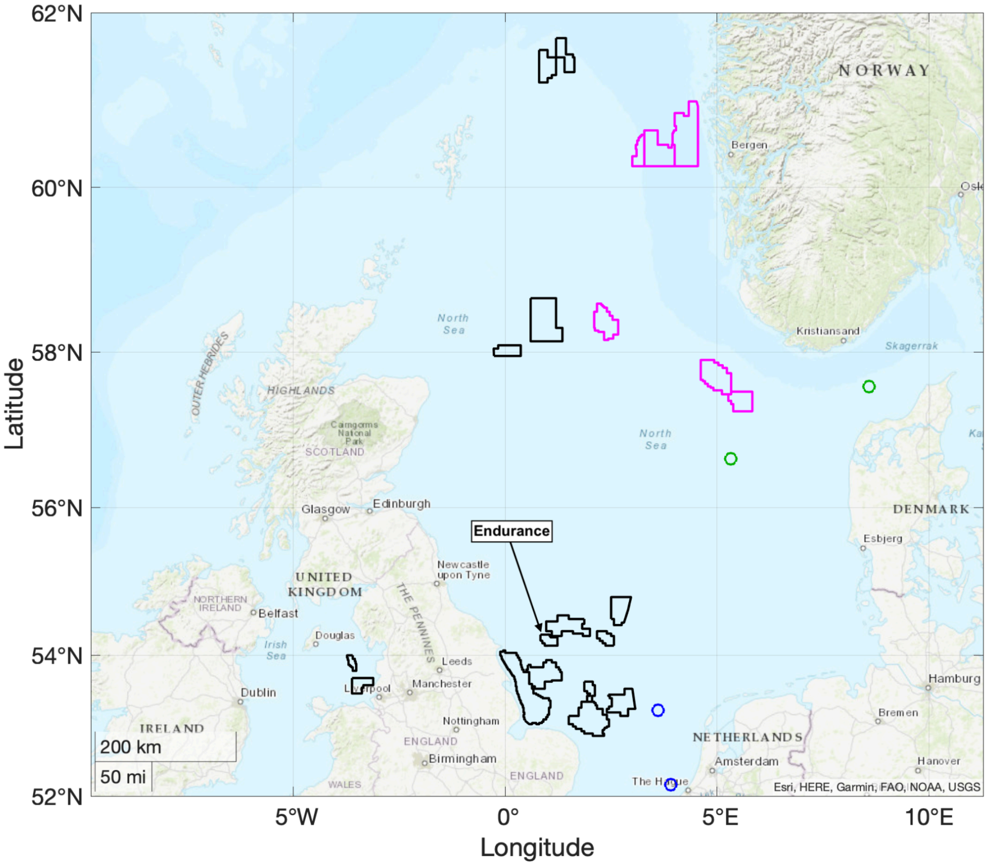

***Figure 1**: Map showing boundaries of CO_2 storage licences (polygons) and location of other operating and nascent storage projects (circles). Licences granted by the UK are shown as black polygons, while those from Norway are shown in magenta. Locations of Danish (green) and Dutch (blue) storage projects and prospects are shown by the coloured circles.*

Operators and regulators require a clear understanding of the rate of natural seismicity to identify and distinguish induced events from natural as well as to assess the likelihood and severity of injection-induced fault reactivation. This requires a dedicated, site-specific background monitoring programme, as well as high quality seismicity data for the North Sea region as a whole. This study has produced the first dedicated combined catalogue of seismicity of the North Sea, based on all available data from each of the relevant seismological agencies. This study reports the dataset, how it was created, and how it is now enabling further studies into seismic hazard, leakage risk, and stress state in a region that will be vital for European CO_2 storage efforts in the coming decades.

Tectonic background

The North Sea is located in a relatively stable tectonic environment. It is far from the mid-Atlantic ridge (MAR) to the west (>1500 km), and the African-Eurasian plate boundary (AEB) is >700 km to the south. Regional scale tectonic stress patterns are controlled primarily by post-glacial rebound, ridge push force from the MAR, and subduction forces from the AEB. Furthermore, residual stress effects are evident in regions affected by the emplacement of magma and subsequent breakup of the North Atlantic Igneous Province in the Paleogene (~62 – 54 Ma). As a result, measures of seismic hazard (e.g., earthquake recurrence rates, peak ground velocity or acceleration) in the region are relatively low when compared to more tectonically active regions globally, though a few large magnitude events have been recorded (~M 6). There is also evidence for larger (M > 7) earthquakes associated with post-glacial rebound north of Norway (e.g., Bungum et al., 2005). Table 1 summarises the largest events that were recorded in the region. It should be noted that all but one of these events occurred before seismic instrumentation was ubiquitous across Europe (from ~1985), and so the sizes and locations of these events have greater uncertainty.

The geologic structure of the North Sea is primarily associated with the triple plate collision that occurred around 450 Ma ago (Late Ordovician to Early Silurian) during the Caledonian Orogeny. However, many of the largest structures in the North Sea that generate present day seismic hazard were created in the Permian and Triassic. Volcanic rifting 250 to 150 Ma ago created horst and graben structures bounded by a series of large normal faults, which are spread across the north of the study region, and formed the Viking Graben. The graben is now oriented N–S and is located around 100 km to the west of Norway. Further rifting in the Late Jurassic through to the Early Cretaceous (160 to 140 Ma ago) created additional extensional structures further to the south, forming the Central Graben. Thermal subsidence in the Cretaceous, igneous activity in the Palaeogene, uplift of the basin margins later in the Cenozoic, and continued uplift and glacial erosion through to the Quaternary resulted in a thick series of sedimentary deposits that buried the Jurassic and Cretaceous rocks that sourced the considerable North Sea oil and gas reserves. More recently (in the last 2.5 Ma), changes in river sediment deposition and sea level, broadly associated with changes in glaciation, produced thick sedimentary sequences in the south of the North Sea. This gave rise to shallow seas over a large area off the east coast of England, in particular the Dogger Bank bathymetric high.

***Table 1**: Events with a reported moment magnitude greater than 5 in North Sea, sorted by moment magnitude. The largest event is located only tens of kilometres from the Endurance CO_2 storage licence (albeit at a depth likely greater than 20 km). The three northernmost events (latitude > 60̊ deg) are probably associated with post-glacial rebound processes.*

Datetime	M_w	M_L	Latitude	Longitude
07/06/1931 00:25	6.0	6.0	54.08	1.5
24/01/1927 05:18	5.7	6.0	59.68	2.7
18/09/1901 01:24	5.4	-	57.5	-4.2
21/03/2022 05:32	5.3	5.0	61.67	2.58
03/06/1955 11:39	5.2	5.0	61.9	4.1
21/08/1967 13:41	5.2	5.0	57.092	4.593
04/04/1961 22:42	5.1	5.0	61.8	1.5

SHARP Storage

This data collection and study was conducted as part of the Accelerating CCS Technologies project SHARP Storage (Stress history and reservoir pressure for improved quantification of CO_2 storage containment risks). SHARP involves investigators from 16 institutions and companies working in 5 countries: Norway, Denmark, the Netherlands, UK, and India (www.sharp-storage-act.eu). This project aims to substantially improve leakage risk management of CO_2 storage operations through several work packages. Geomechanical modelling, laboratory experiments, seismology, and probabilistic risk assessment is being integrated by a broad mix of industry and academic partners. The project will conclude in 2024, providing guidance for CO_2 storage operators and regulators on reservoir pre-characterisation, modelling, monitoring, and risk quantification.

Data collection and curation

Seismicity data has been aggregated from the global database (of the International Seismological Centre, ISC) and seismological agencies in the region: the British Geological Survey (BGS); the Royal Netherlands Meteorological Institute (KNMI); the Geological Survey of Denmark (GEUS); the Norwegian National Seismic Network (NNSN); NORSAR; the German Institute for Geosciences and Natural Resources (BGR); the GEOFON programme of the German Research Centre of Geosciences

(GFZ); and Christian-Albrechts University (CAU) in Kiel. Whilst a number of these agencies do share some data between them, this study represents the first effort to wholly combine all available earthquake data in the region up to the end of 2021.

A polygonal area was chosen to capture only events that occur in the North Sea (Figure 2). Once events within the polygon were retrieved from each of the above agencies, an extensive process of database merging and cleaning was conducted. Firstly, erroneous events or data entries were removed from the dataset. Subsequently, several methods were used to find duplicate events in the initial merged dataset. Events that coincided in both space and time within defined thresholds were merged (following Jones et al., 2000; Jónasson et al., 2021), along with those that shared similar phase arrival times at the same seismic stations. Many marginal duplicate event candidates were manually inspected as a further quality control step. After the merging, an event association was performed, before an algorithm was applied to remove functionally duplicated, but non-identical, phase and origin information. Once the filtering was completed, each time and location entry was given a unique identifier, which embeds the agency from which the data originated.

Known and suspected explosions were identified and marked in the catalogue, such that further studies can exclude them. This was primarily done through comparisons of the individual agency's lists of known explosions. Some agencies mark events in their respective catalogues as suspected explosions based on location, size, time of occurrence, and waveform type. Others also communicate with their corresponding national defence agencies, who report when and where munitions are detonated, allowing the seismological agencies to mark detected explosions with certainty (e.g, Ruigrok et al., 2019). In the combined catalogue, a relative increase in event number during daytime compared to nighttime can be readily observed, indicating that the excess likely consists of explosions.

In collecting and storing the event and seismic phase data for distribution, we use the standard International Association of Seismology and Physics of the Earth's Interior (IASPEI) Seismic Format (ISF; detailed in IDC, 1999). When this information is combined into a single file, these data are referred to as a "bulletin". A bulletin can have multiple entries for event time and location, reflective of the different seismic networks or methods used by different agencies to detect and locate earthquakes. A simplified version of bulletin data, showing just a single time, location, and size (i.e., magnitude) for each event is referred to as a "catalogue". Waveforms for events with magnitudes greater than M 3.5 have been collected for various analyses, which are discussed further in the "Conclusions and future work" section.

Along with event and phase data, focal mechanism (FM) data were also compiled in this study. The primary project aim is to better constrain the regional stress field, and thus slip orientation data are a critical component. Furthermore, velocity models for the North Sea were compiled from several of the above agencies as well as the CRUST1.0 model (Laske et al., 2013). These velocity models are used primarily by the seismological agencies for the localisation of events through travel time inversion, but are also required for further studies (as detailed in the "Conclusions and further work" section).

Results

After the filtering and cleaning process described above, the catalogue consists of 15,231 events, with 3223 identified as (suspected) explosions. The bulletin comprises 43,730 individual entries for origin time and location. In the subsequent figures, we present the prime (i.e., the first) entries. The compiled FM catalogue consists of 60 solutions from 50 different events.

Figure 2 shows a map of the event catalogue, and clearly demonstrates the spatial variability in both the seismicity rates and detection thresholds in different parts of the North Sea. The Viking and Central graben regions (annotated in Figure 2) have a higher seismicity rate, as expected, with generally larger events compared to most of the central North Sea. Also as expected, detection and location of smaller magnitude events ($M<3$) is greater near the coast due to proximity to the national seismic networks. Detection thresholds are particularly low (with $M<1$ detected) close to the Norwegian coast, due to the greater coverage of seismic stations operated by the NNSN through the last three to four decades, the higher seismic activity rate close to the Viking graben, and the multiple seismic arrays that are operated by NORSAR (see Schweitzer et al., 2021). Since the installation of the Equinor-owned, NORSAR-operated HNAR array in 2020, the detection threshold is expected to have further decreased in this area (Zarifi et al., 2023) .

Figure 3 displays the magnitudes of catalogued events through time. It clearly demonstrates the changes in the detection thresholds, with historical seismicity (pre-1900) usually much larger than M 4, the routine detection of $M>4$ from 1900, and the significant improvement in detection capability from 1980. The magnitude of completeness M_{min} (the magnitude above which all events are reported) clearly varies through time, but, as indicated in Figure 2, also varies strongly in space. Events with $M<3$ are still unlikely to be routinely detected by national networks in areas far (>200 km) from any coastline (i.e., in the central North Sea).

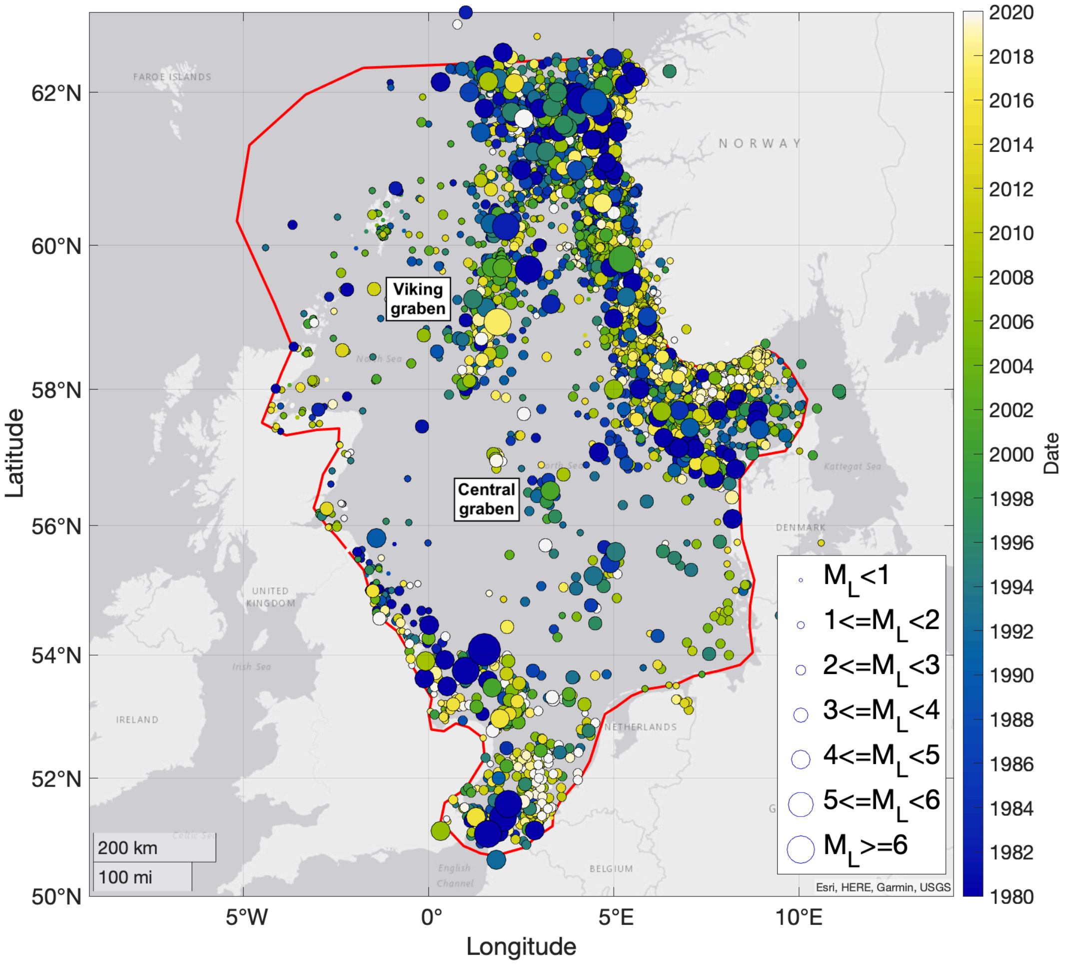

Figure 2: *Map depicting the events in the seismic catalogue, with event epicentres given by circles sized by local magnitude. Marker colour denotes the events' origin times. The red polygon shows the boundary region used for the North Sea. The colour scale is limited to 1980-2020 for contrast. Differences in event detection capability are clearly visible, as well as the higher seismicity rates in the Central and Viking Grabens.*

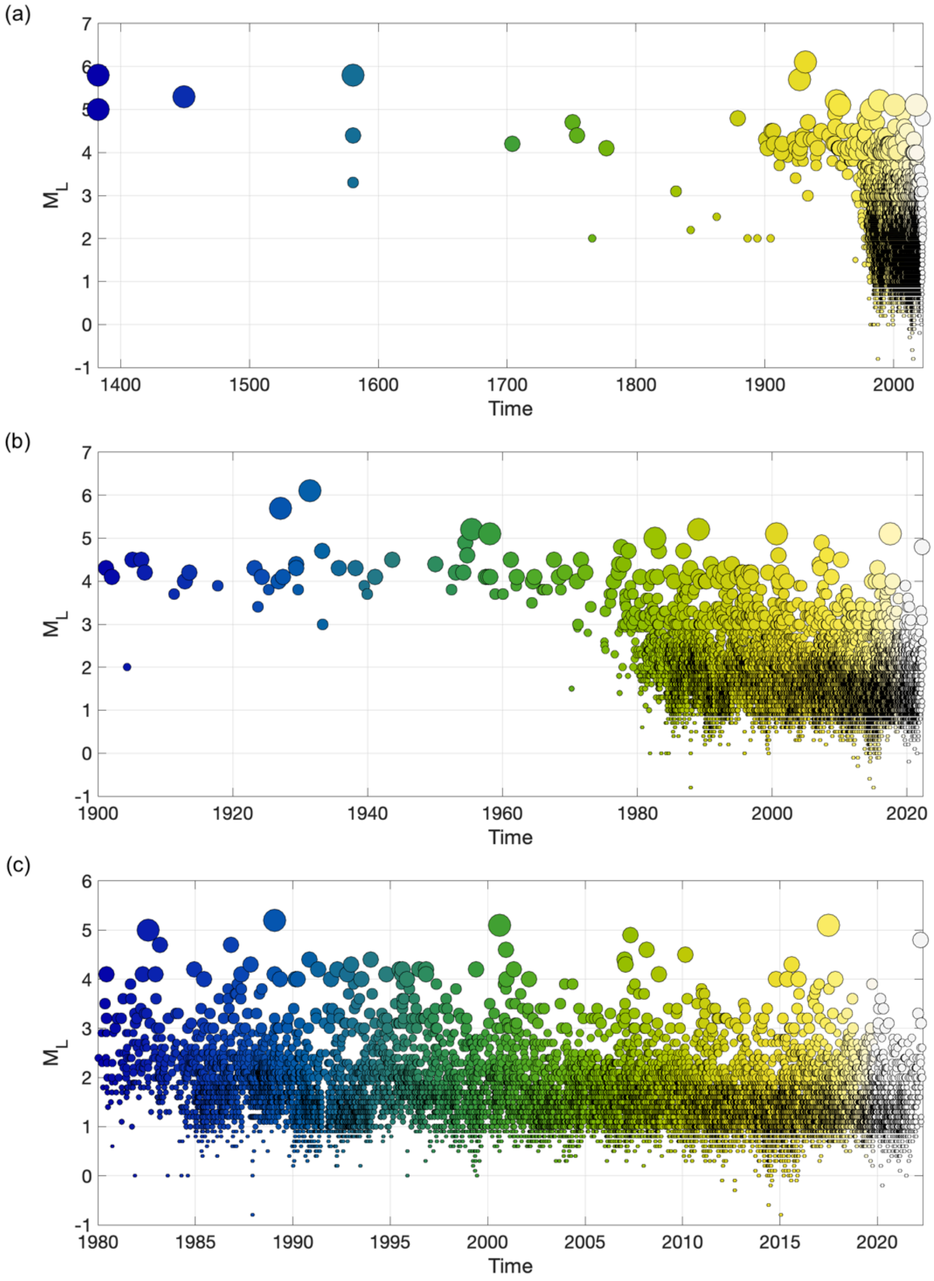

Figure 3: *Local magnitude of catalogued events through time. Note the decreasing time scales, which range from the earliest events in the catalogue (May 1382) in (a), to the advent of dedicated instrumental earthquake measurement in the region (from around 1900 on) in (b), to the modern era of earthquake detection and location (from 1980) in (c). There are clear changes in detection ability through the different time periods, representing an improvement in the magnitude of completeness for the catalogue.*

Figure 4 shows the magnitude-frequency distribution for the events, together with the estimated Gutenberg-Richter (GR) b-value. This empirical GR relationship – *log(N) = a-bM* – relates the number of events *N* above the magnitude of completeness M_{min} to the magnitude *M*, with *b* characterising the slope of the line in log space and *a* being the overall activity rate. Figure 4a shows the calculated b-value for the current catalogue when applying the stability method of Cao and Gao (2002) to estimate M_{min}, resulting in a notably low value of *b* = 0.8±0.02. Lower b-values suggest a greater than expected number of large earthquakes relative to the number of small ones, and thus an increased seismic hazard in the region. However, the estimated M_{min} of around M 1.5 is likely to be too optimistic due to the spatiotemporal variability of detection thresholds in the North Sea. In fact, the kink in the magnitude distribution, which is visible around M_L 3.5, is indicative of the variations in detection thresholds across both space and time, and potentially the differing magnitude scales used in the region. A reasonable estimate of M_{min} for the entire catalogue would be around M 4, which produces a b-value of 1.0±0.2, comparable to many tectonic settings around the world (Figure 4b). Along with a thorough spatiotemporal analysis of M_{min}, homogenisation of magnitudes is a goal of the subsequent work of the SHARP project.

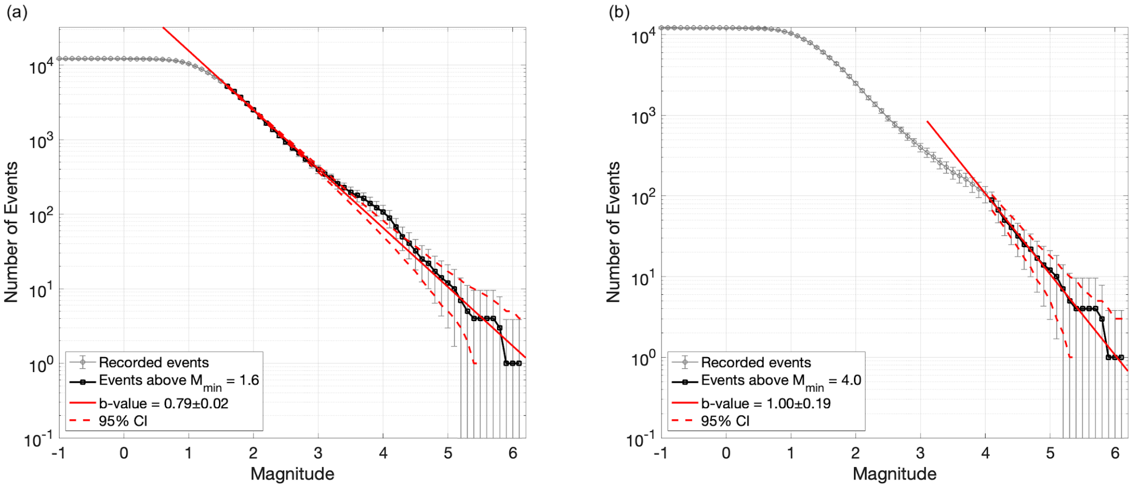

Figure 4: *Magnitude-frequency distribution for the catalogue using local magnitudes. Gutenberg-Richter b-value is measured using the maximum likelihood approach of Aki (1965). (a) shows the b-value found when the b-value stability method of Cao and Gao (2002) is used to find the magnitude of completeness* M_{min}*. (b) shows the b-value when a more realistic* M_{min} *of* M_L *4 is imposed.*

Conclusions and future work

This enhanced North Sea seismicity catalogue will enable a greater understanding of not only earthquake occurrence in the region, but also fault locations and orientations, in situ stress state, and fracture density. Seismicity data as collected in this study are a clear asset to CO_2 storage and offshore wind farm operators as well as regulators in assessing environmental risks associated with prospective projects, quantifying earthquake hazard, and identifying induced seismicity.

Producing a combined and cleaned seismological dataset is also of great interest for academic communities in developing new methods and reanalysing a more complete record of earthquake origins and phase readings. Those interested in North Sea earthquake source processes and hazards can use this dataset with confidence that this is the collection of all available data, from every agency which routinely records seismicity in the region. This is particularly novel for an offshore region with many overlapping agencies, and grants an opportunity to improve derivatives of this data by bringing together all available recordings of events.

The SHARP project consortium is continuing with the analysis and improvement of this combined data using numerous methods. The catalogue is being relocated using the newly combined list of phase readings from various seismic networks. This relocation method uses a probabilistic framework, sampling each of the possible origins from different velocity models to better constrain locations and associated uncertainties (see Schweitzer, 2001; 2018). Also using the enhanced spatial coverage, new focal mechanisms are being inverted using a Bayesian bootstrap-based probabilistic joint inversion scheme (see Heimann et al., 2018). This study is focussing on the areas around nascent CO_2 storage developments, in order to be used in stress inversion studies. Further, event magnitudes are being homogenised.

Stress drop measurements will be derived using an empirical Green's function approach, using the increased coverage to give more accurate stress drops with better constrained uncertainty (using the method of Goertz-Allmann et al., 2011). These results in particular will be integrated in the definitions of stress in and around the prospective CO_2 storage reservoirs, and the larger geomechanical modelling studies (as in Angus et al., 2010) of SHARP.

Ground motion prediction equations (GMPEs) are being derived for the onshore regions nearest the development CO_2 storage projects, and an updated probabilistic seismic hazard analysis is being carried out on a regional scale. Results will be compared with the existing national hazard models and local scale studies of seismic hazard, providing an updated and comparable assessment of seismic hazard based on this newly analysed data set.

The SHARP program is also assessing the suitability and efficacy of the myriad of environmental monitoring technologies that could be used in the North Sea for CO2 storage. This includes active seismic, offshore passive microseismic, land-based microseismic arrays, ocean bottom seismic (OBS), distributed acoustic sensing (DAS), large-N permanent reservoir monitoring (PRM). This includes the ability for these technologies to detect earthquakes, locate them, determine their depth, and to distinguish induced from natural seismicity.

Each of these activities will feed into a larger analysis, improving quantification of risks to CO2 storage integrity, and the understanding of the state of stress and faulting in an area that will host many CO_2 storage and offshore wind projects in the coming decades. This data and the subsequent work will significantly aid in quantifying risks from seismicity, induced seismicity identification, and storage integrity assessment. Each of these are key to facilitating the development and management of industries that are urgently needed to combat climate change.

Data availability

This seismic catalogue is currently (as of July 2023) available from the authors upon request. Once the SHARP project has been completed (December 2024), the final, improved catalogue will be made publicly available via the ISC data repository.

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