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De-risking European CCS operations with the most complete earthquake catalogue for the North Sea

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Summary

With the development of several CO_2 storage operations in the North Sea, there is a clear need to better characterise the seismic hazard and stress state in the region. Faults and associated fracture sets can act as hydraulic pathways for unintended CO_2 migration, ill-defined stress states can lead to numerous operational difficulties, and induced seismicity will be a clear risk as CO_2 is injected into subsurface reservoirs. Seismicity can reveal the location and extent of faults and fractures, and can be used to invert for the state of stress. Both operators and regulators therefore need a clear understanding of the rate of natural seismicity, to identify and distinguish induced events from natural, and to assess the likelihood of induced fault reactivation. This requires a dedicated, site specific background monitoring programme, as well as a high-quality seismic catalogue for the region around any CO_2 storage operation. Our study has produced the first dedicated seismic catalogue of the North Sea, based on all available data from each of the relevant seismological agencies. This dataset fosters 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.

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Introduction

Despite seismic hazard in the North Sea being comparatively low, it is critical to assess the rate and size of local earthquakes as CO_2 storage operations are being developed. Seismicity 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. Also, the faulting style of seismic events directly relates to the in situ stresses. Stress measurements inferred from faulting style (i.e., stress inversion) can be compared to both borehole stress measurements and stresses estimated using other seismological methods such as stress drop or anisotropy analysis. Seismicity-derived stress measures can therefore provide a more robust and complete assessment of the regional and local state of stress, which is vital for the long-term injection of CO_2 in a safe and secure manner.

The risk of injection-induced seismicity is also present for these operations. Both operators and regulators therefore need a clear understanding of the rate of natural seismicity, to identify and distinguish induced events from natural, and to assess the likelihood of induced fault reactivation. This requires a dedicated, site specific background monitoring programme, as well as a high-quality seismic catalogue for the region around the CO_2 storage operation. Our study has produced the first dedicated seismic catalogue of the North Sea, based on all available data from each of the relevant seismological agencies. This dataset fosters 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.

Data collection and curation

Seismic bulletins have 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 for Geosciences (GFZ); and the Christian-Albrechts University (CAU) in Kiel. Whilst a number of these agencies share data between them, this study represents the first effort to exhaustively combine available earthquake data in the region up to May 2022.

A polygonal area was chosen to capture only events that occur in the North Sea. The polygon is depicted as a red line in Figure 1. After 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 duplicated events in the initial merged dataset. Events that were coincident in both space (within 1°) and time (within 30 s) 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 (within 2 min) were manually inspected, as a further quality control step. After this event association, 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 that also denotes the agency from which it originated.

For collection, storage, and distribution of the collected seismicity data, we use the International Association of Seismology and Physics of the Earth’s Interior (IASPEI) Seismic Format (ISF) – the standard for the distribution of earthquake origin times, locations, and seismic phase information. A collection of single event data sets combined into a common file are called a “bulletin”. A single event can have multiple entries for event time, location, and magnitude, reflective of observations or methods used by different agencies and locate earthquakes. A simplified version of the bulletin, limited to a unique source time, location, and magnitude for each event are referred to as “catalogue”. Presently, all events are being relocated and waveforms for a significant subset of the events are being collected.

Results

After the filtering and cleaning described above, the bulletin consists of 15,230 events, of which 5,408 were identified as likely or potential explosions. This is comprised of 43,730 individual entries for origin times and locations. We extract the prime (i.e., the first) entry to obtain a single location and magnitude for each event in the subsequent figures.

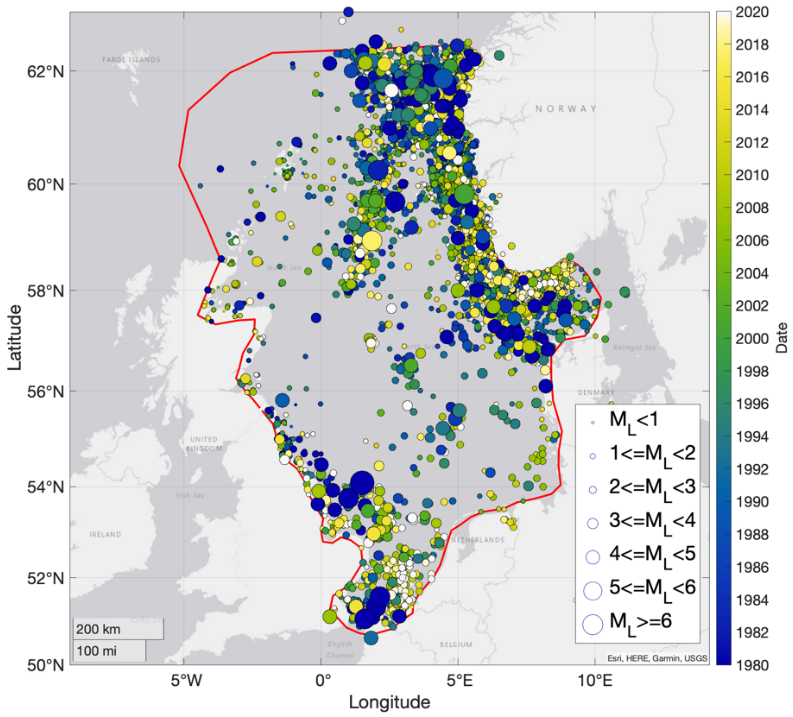

Figure 1 *Map showing the seismic event catalogue (prime entries of the event bulletin), with event epicentres given by circles sized by local magnitude. Marker colour denotes the time in which the events occur. The colour scale is limited to after 1980 for contrast. Differences in event detection capability are clear, as well as the higher seismicity rates in the Central and Viking Grabens.*

Figure 1 shows a map with the catalogued events. It 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 region have a higher seismicity rate, as expected, with generally larger events occurring in the region when compared to most of the central North Sea. Also as expected, detection and location of smaller (M<3) events is greater near the coast due to proximity to the national seismic networks. Detection thresholds are particularly low (M<1) along the Norwegian coast, due to the greater coverage of seismic sensors operated through the last three to four decades by NNSN, and the multiple seismic arrays that are operated by NORSAR.

Figure 2 shows the magnitudes of catalogued events through time. This clearly demonstrates the changes in the detection thresholds, with historical seismicity (pre-1900) usually much larger than M 4, the routine detection of M>3.5 from 1900, and the significant improvement in detection capability from 1980. This magnitude of completeness M_c (the magnitude above which all events are reported with certainty) clearly varies through time, but as shown in Figure 1, also 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 3 shows the magnitude-frequency relation for the events, with the measured Gutenberg-Richter (GR) b-value. This empirical GR relationship – $log(N) = a - bM$ – relates the number of events N to the magnitude M, with b characterising the slope of the line in log space, and the overall activity rate given by a. Figure 3a shows the b-value when the stability method of Cao and Gao (2002) is used to estimate the magnitude of completeness, giving a notable low value of 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 a significant underestimate, due to the spatiotemporal variability of detection thresholds in the North Sea. However, a kink in the magnitude distribution is visible around M_L 3.5. This 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} around 4 produces a b-value of 1.0±0.2, which is similar to b-values reported for similar tectonic settings around the world. Along with a thorough magnitude of completeness analysis, homogenisation of the magnitudes is a clear next step of the subsequent work on the catalogue.

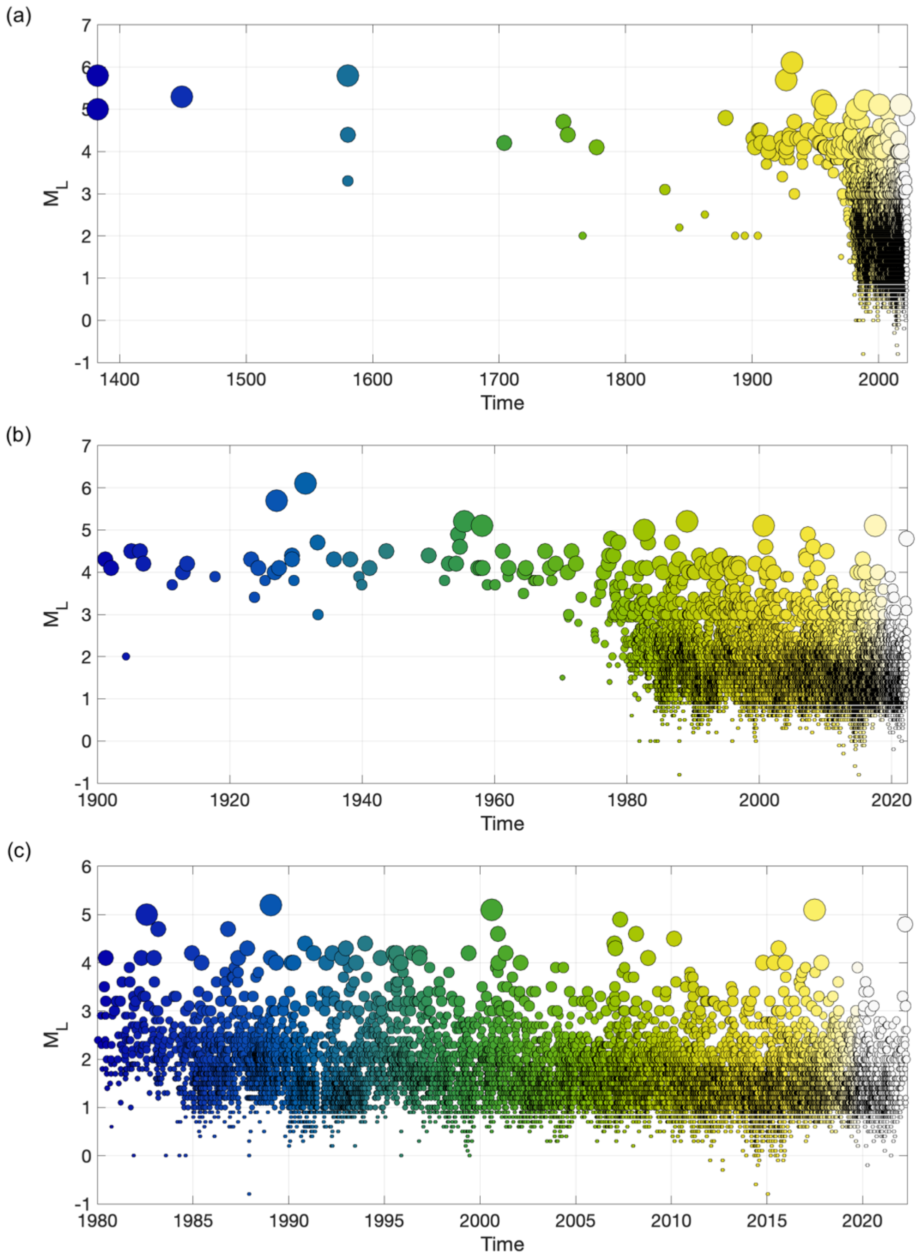

Figure 2 *Local magnitude of catalogued events through time. Note the decreasing time scales, which range from the earliest events in the catalogue (May 1382) in (a), to the advent of dedicated instrumental earthquake measurement in the region (from around 1900) in (b), to the modern era of earthquake 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.*

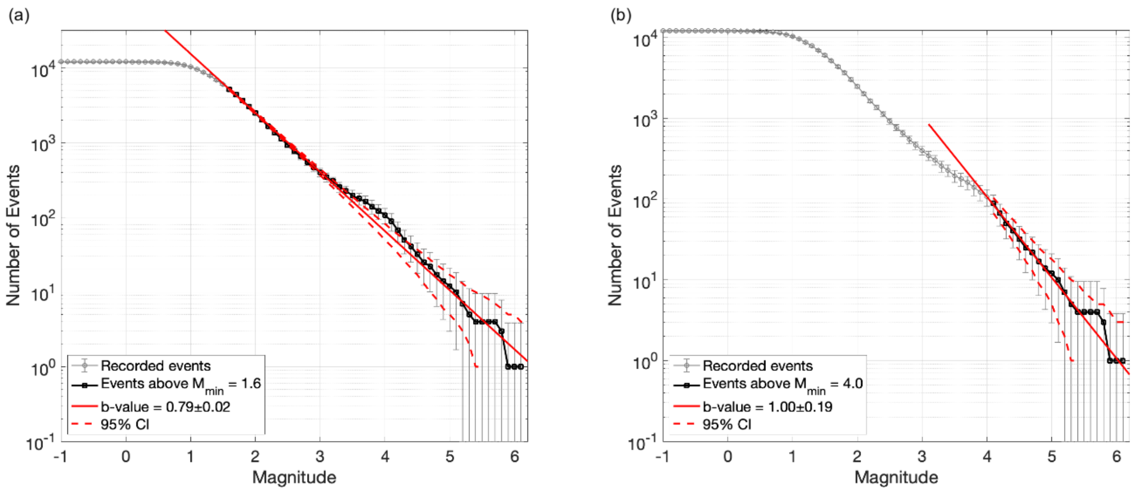

Figure 3 *Magnitude-frequency distribution for the catalogue using local magnitudes. Gutenberg-Richter b-value is measured using the maximum likelihood approach of Aki (1965). (a) shows the b-value found when the b-value stability method of Cao and Gao (2002) is used to find the magnitude of completeness* M_{min}*. (b) shows the b-value when a* M_{min} *of* M_L *4 is imposed.*

Conclusions and future work

Our catalogue of North Sea seismicity will enable a greater understanding of not only earthquake hazard in the region, but also fault location and orientation, in situ stress state, and fracture density. This will be an asset for both CO_2 storage operators and regulators in assessing prospective projects. The project is continuing with the analysis and improvement of this newly combined data using numerous seismological methods, such as event relocation, focal mechanism inversion, stress drop measurements, ground motion prediction equation derivation, and probabilistic seismic hazard analysis.

Data availability

The seismic catalogue and associated processing codes are currently (as of January 2023) available from the authors upon request. Once the project has been completed, the final improved catalogue will be made publicly available via the ISC.

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