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History of monitoring induced seismicity in New Mexico

Mairi Litherland
New Mexico Bureau of Geology and Mineral Resources, New Mexico Institute of Mining and Technology, 801 Leroy Place, Socorro, New Mexico 87801, USA

ABSTRACT

New Mexico has experienced earthquakes throughout its history. Paleoseismic records show numerous Quaternary faults along the Rio Grande Rift, which runs N-S through the state, and events as large as ~M 6.2 have occurred associated with the Socorro magma body in central New Mexico. In recent years, the state has also experienced increased amounts of induced seismicity. Because of its long history of naturally occurring earthquakes, New Mexico began monitoring earthquakes in 1960, primarily around the Socorro area. In 1972, the New Mexico Institute of Mining and Technology established a seismic monitoring network in southeastern New Mexico to monitor seismicity in the region of the proposed Waste Isolation Pilot Plant, a nuclear waste storage facility. A permanent network was established in the 1990s, and it has been expanded and improved several times over the subsequent decades as the seismicity in the region has increased. Currently, the New Mexico Tech Seismological Observatory maintains 17 real-time stations throughout the state of New Mexico, primarily in the Socorro area and in southeastern New Mexico. The University of New Mexico, Los Alamos National Laboratory, U.S. Geological Survey, and the state of Texas maintain additional stations in and around New Mexico. Although the amount of induced seismicity in New Mexico has been to this point relatively moderate, the rapid increase in seismicity, particularly in the Permian Basin in southeastern New Mexico, has given rise to concerns about what the future could hold and led to increased efforts to understand the seismicity. Due to the location of New Mexico's major oil- and gas-producing basins, several of which span state borders, collaboration with other states and agencies has been essential to studying these problems. Additionally, the long history of seismic monitoring in southeastern New Mexico provides an invaluable resource for understanding the progression of induced seismicity over time. We have only begun to fully utilize the potential of this data set.

INTRODUCTION

Motivation

New Mexico is one of the leading oil- and gas-producing states in the United States. Energy production is an important part of New Mexico's economy; however, the ongoing rise in induced seismicity in southeastern New Mexico associated with oil and gas production has prompted concern from regulators and the public. The increase in seismicity in southeastern New Mexico is associated with an increase in fluid disposal (Fig. 1), similar to that recorded in other areas with induced seismicity

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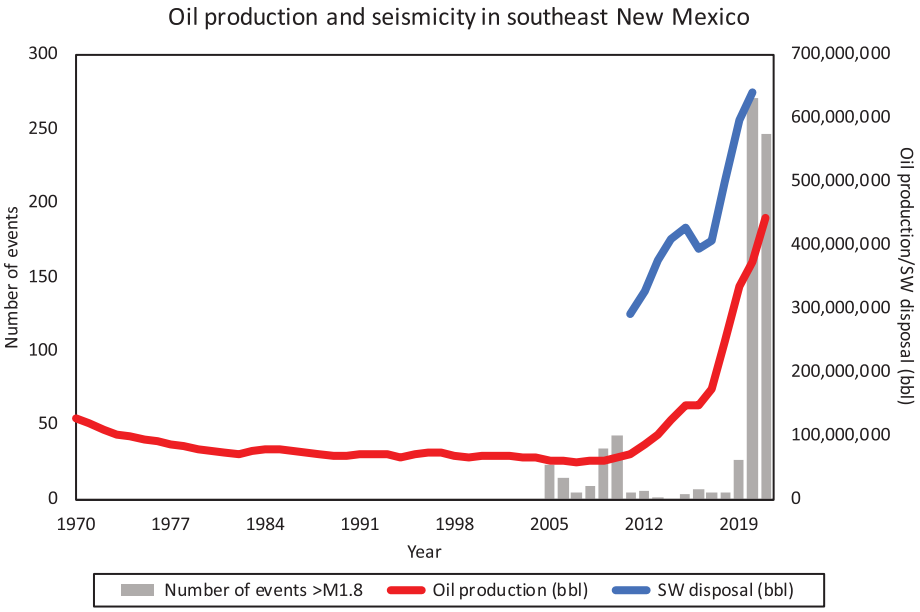


Figure 1. Oil production and seismicity in southeast New Mexico. Red line shows yearly oil production in New Mexico from 1970 to 2021 (bbl); production was steady during this period until 2010, when production increased significantly. Blue line shows yearly saltwater (SW) disposal in southeastern New Mexico from 2011 to 2020 (value for 2020 is estimated; water disposal data are from Rinehart et al., 2020). Gray bars show number of earthquakes larger than M 1.8 recorded in southeastern New Mexico by the New Mexico Tech Seismological Observatory (NMTSO) from 2005 to 2021.

(e.g., Keranen et al., 2014). Additionally, in the Texas portion of the Permian Basin, Savvaidis et al. (2020) showed that some earthquakes are more likely to have been induced by hydraulic fracturing rather than fluid disposal, though the specific causes of induced seismicity in New Mexico are not currently known.

Seismic monitoring networks in New Mexico have been critical tools for identifying the issues and understanding the connection between seismicity and fluid injection. This has allowed the development of new regulatory frameworks to mitigate induced seismicity. However, continued improvements to the network are necessary to widen the availability of near-real-time data for public information and regulatory decision-making, and additional research and analyses are needed to answer questions about induced seismicity in New Mexico.

History of Oil and Gas Production in New Mexico

The first discovery of natural gas in New Mexico occurred in 1921 in the San Juan Basin in northwestern New Mexico, and the first commercial oil production began in 1922, also in the San Juan Basin. In 1924, the Artesia field was discovered in southeastern New Mexico, and more discoveries quickly followed (Broadhead, 2017). Oil production in New Mexico rose until around 1970 and then steadily declined until the mid-2000s, when production rose sharply. This was in part due to the adoption of unconventional recovery techniques, such as hydraulic fracturing and directional drilling, which enabled the extraction of oil that could not be recovered using traditional drilling methods (Fig. 1; Broadhead, 2017). In 2021, New Mexico produced ~440 million barrels of oil, its largest ever total according to the New Mexico Oil Conservation Division (New Mexico Energy, Minerals, and Natural Resources Department, 2022). This was the second most of any state, behind only Texas.

Over 97% of the oil produced in New Mexico comes from the Permian Basin in southeastern New Mexico. Approximately 20% of the Permian Basin is in New Mexico, with the remainder being in Texas. Oil- and gas-producing formations in New Mexico include the Northwest Shelf, the Central Basin Platform, and the Delaware Basin. Since 2010, oil production in the New Mexico portion of the Permian Basin has increased by over six times. This rise has been accompanied by an increase in the amount of produced water that must be disposed of, more than doubling since 2011 to over 600 million barrels (Fig. 1; Rinehart et al., 2020).

Most of the remainder of the state's oil production is from the San Juan Basin in northwestern New Mexico, which lies across the New Mexico–Colorado border, with 90% of the basin being in New Mexico. The San Juan Basin produces primarily natural gas, historically accounting for more than half of the state's natural gas production, but producing only a quarter of the total for 2020, primarily due to the increase in production in the Permian Basin.

The Raton Basin, in northeastern New Mexico, was historically a coal-producing region, with coal having been first discovered there in 1821 and mined commercially since 1870 (Osterhout et al., 2014). In 1994, coalbed methane extraction began in the Colorado portion of the Raton Basin, and in 1999, it began in the New Mexico portion (Hoffman and Brister, 2003). Coalbed methane extraction produces large amounts of water, which is typically injected back into the ground. Water injection in the New Mexico portion of the Raton Basin averaged ~14 million barrels/yr between 2004 and 2014 (Rubinstein et al., 2014), but it has declined somewhat since that time (Glasgow et al., 2021).

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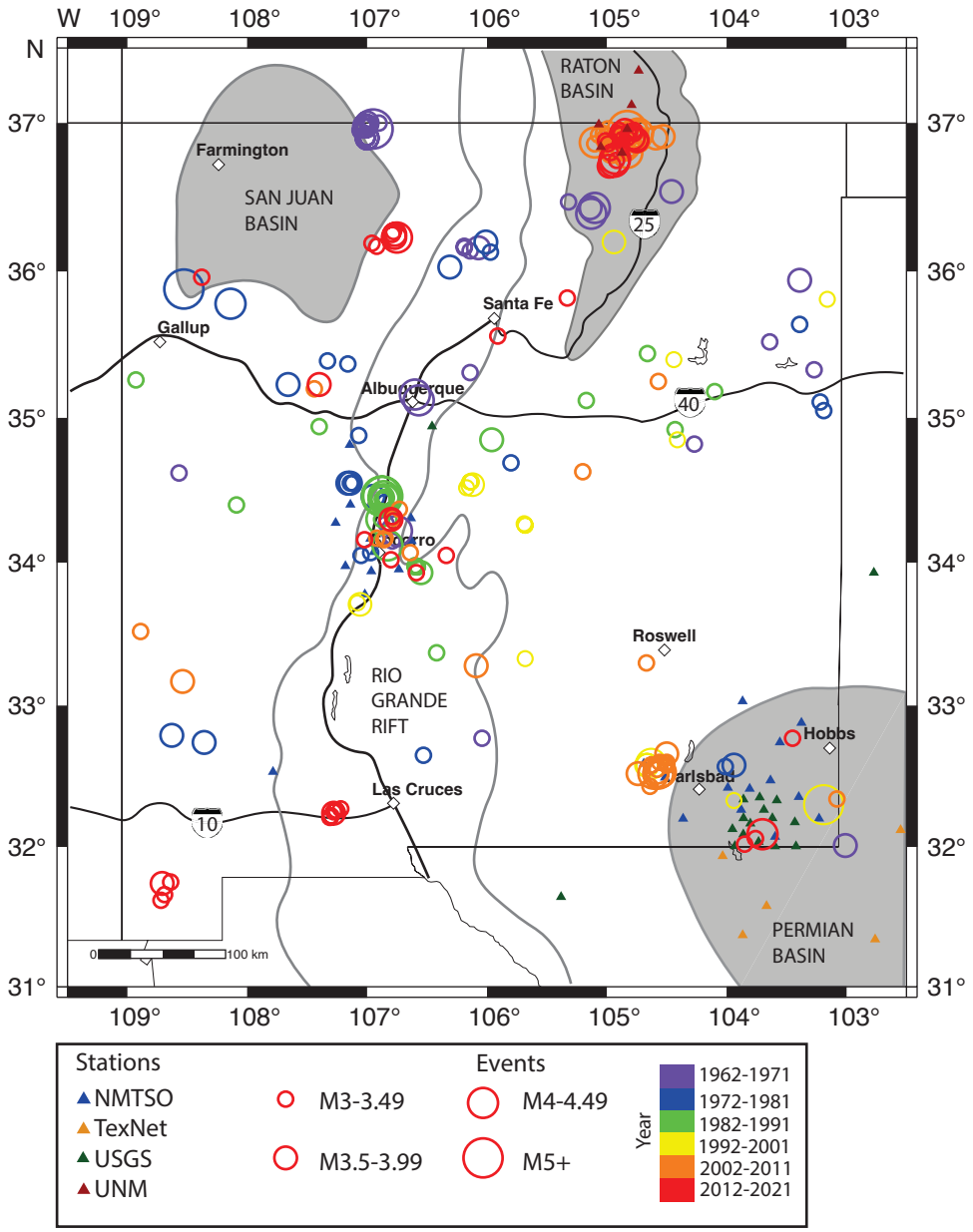


Figure 2. Map showing three major oil- and gas-producing regions of New Mexico: the Permian Basin, the Raton Basin, and the San Juan Basin (shaded gray), as well as the Rio Grande Rift (outlined in gray). Earthquakes >M 3.0 from the New Mexico Tech Seismological Observatory (NMTSO) and U.S. Geological Survey (USGS) catalogs are shown for the period 1962–2021; the magnitude of the event is represented by the size of the circle, and the age of the event is represented by its color. Publicly available seismic monitoring stations in New Mexico and selected stations from neighboring states are represented by triangles, colored by the owner of the network. UNM—University of New Mexico.

SEISMICITY IN NEW MEXICO

Naturally Occurring Earthquakes in New Mexico

New Mexico has long experienced earthquakes in different parts of the state (Fig. 2). Many of these earthquakes occurred along the Rio Grande Rift, an extensional tectonic province that extends from Colorado through New Mexico and into northern Mexico. Seismicity has also been observed along the Jemez lineament, an E-W–trending chain of volcanic fields in northern New Mexico. The Socorro magma body in central New Mexico accounted for ~23% of the state's M 2.0 or larger events prior to the widespread occurrence of induced seismicity in the state (Sanford et al., 2002). The largest known earthquake to occur historically in New Mexico was recorded on 15 November 1906 in Socorro, New Mexico, with an estimated magnitude of 6.2 (Sanford, 2008). It was part of a swarm of events that also included two other (preshock) events larger than M 5.5 that occurred in July of that year. The largest historic earthquake in northern New Mexico occurred near Cerrillos, New Mexico, with an estimated magnitude of 5.25 (Olsen et al., 1979), and the largest historic earthquake that has occurred in or near New Mexico was the M 7.5 Sonora, Mexico, earthquake of 1887 (Suter, 2015). The paleoseismic record shows evidence of numerous large Quaternary faults, and probabilistic hazard studies have concluded that there is a risk of an ~M 7.5

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earthquake in the central Rio Grande Valley, which is the location of the largest population center in New Mexico (Wong et al., 2004). Prior to ca. 2000, most of the seismicity recorded in New Mexico was naturally occurring, and New Mexico is characterized as having a moderate level of seismic hazard by the U.S. Geological Survey (USGS) based on its naturally occurring rate of seismicity.

Pre-Instrumentation Earthquakes in the Permian Basin

In the early 1970s, a nuclear waste disposal site called the Waste Isolation Pilot Plant (WIPP) was proposed to be established ~42 km east of Carlsbad, New Mexico. Researchers at the New Mexico Institute of Mining and Technology conducted a seismic hazard analysis of the proposed site,

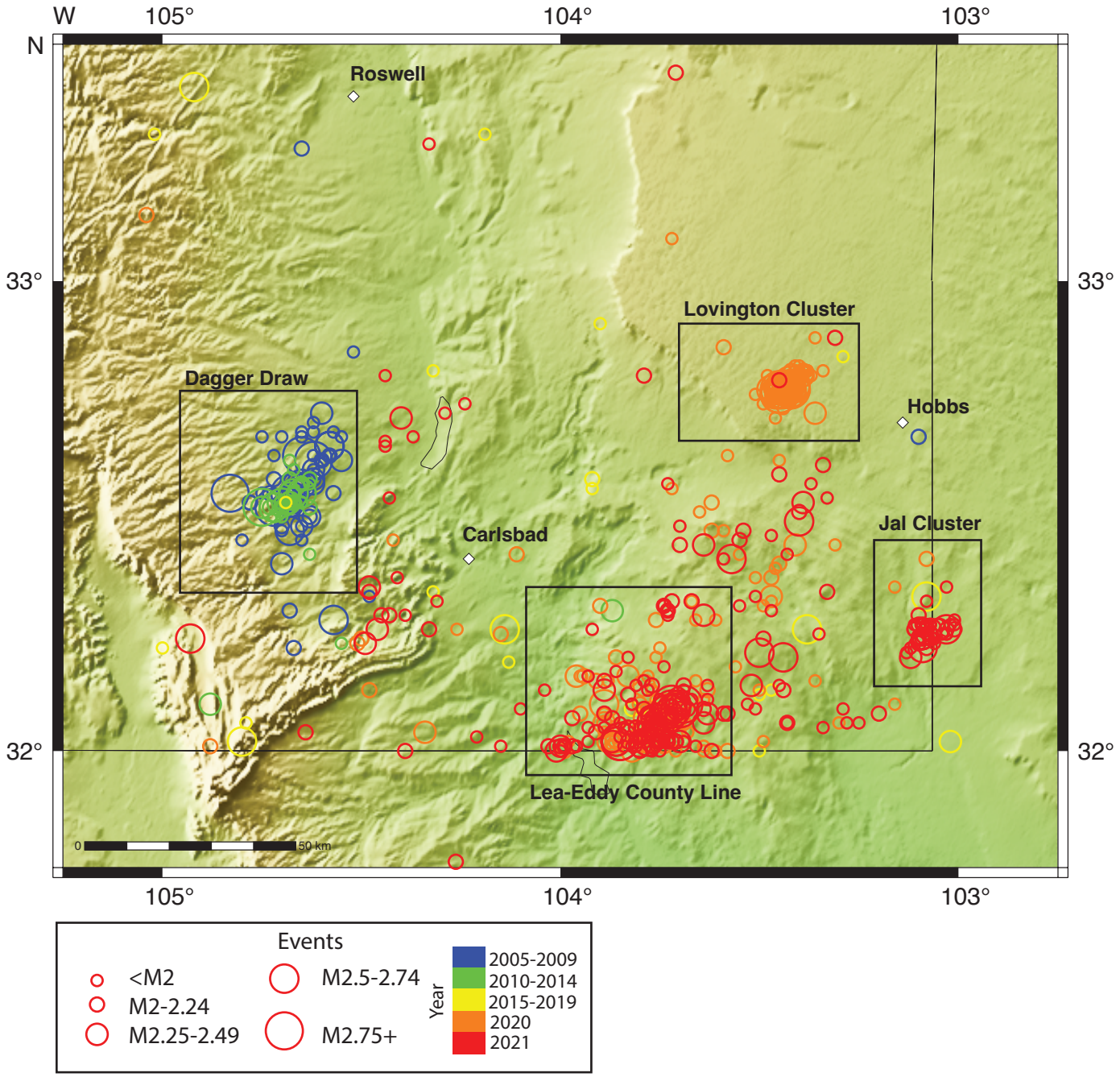


Figure 3. Map of earthquakes larger than M 1.8 recorded by the New Mexico Tech Seismological Observatory in southeastern New Mexico from 2005 to 2021. The magnitude of the event is represented by the size of the circle, while the age of the event is represented by its color. Events are divided into four major clusters; see Figure 4 for time progression of clusters.

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beginning with investigating felt reports of induced seismicity within 300 km. The earliest reported felt event occurred near El Paso, Texas, in 1923 with a maximum intensity of V on the modified Mercalli (MMI) scale (Sanford and Toppozada, 1974). This event occurred in conjunction with a significant population increase in the area due to early oil and gas exploration. Between 1923 and 1961, 20 earthquakes were reported in the region. By 1961, there were sufficient regional seismic stations to instrumentally locate earthquakes in this area, and between 1961 and 1972, 34 earthquakes were located in southeastern New Mexico and west Texas. These earthquakes were mostly distributed in a similar pattern to the earthquakes from the previous felt reports, except for a concentration of events in the Central Basin Platform. Although there were no felt reports of earthquakes in the Central Basin Platform prior to 1965, this was an area with very low population density, so it is possible that undetected events occurred prior to that time. Nonetheless, the Central Basin Platform was an area of active oil and gas exploration and water injection during that time period, and it is likely that these events were induced (Frohlich et al., 2016).

Recent Permian Basin Seismicity

The first notable sequence of seismicity in the New Mexico portion of the Permian Basin occurred in the Dagger Draw oil field northwest of Carlsbad, New Mexico, at an average depth of 11 km. Oil production in this field began in 1969, though both oil and water production were low until the 1990s. Peak production occurred in 1990, with ~10 million barrels of oil and 30 million barrels of water produced (Zhang et al., 2016). Much of this water was reinjected into the Ellenburger Group, which lies just above the Precambrian basement at ~4 km depth. The increase in seismic activity did not begin until 1999, around 4 years after the peak of injection. The cluster of seismicity occurred ~15 km to the west of the Dagger Draw oil field, suggesting that significant fluid migration likely occurred before causing fault slip (Zhang et al., 2016). The largest event in this area was a M 4.1 event that occurred on 28 March 2010. After 2000, production in the field significantly declined, and seismicity in the area dropped to baseline rates by 2013 (Figs. 3 and 4). Currently, New Mexico is no longer permitting disposal wells into the Ellenburger Group (Lemons et al., 2019).

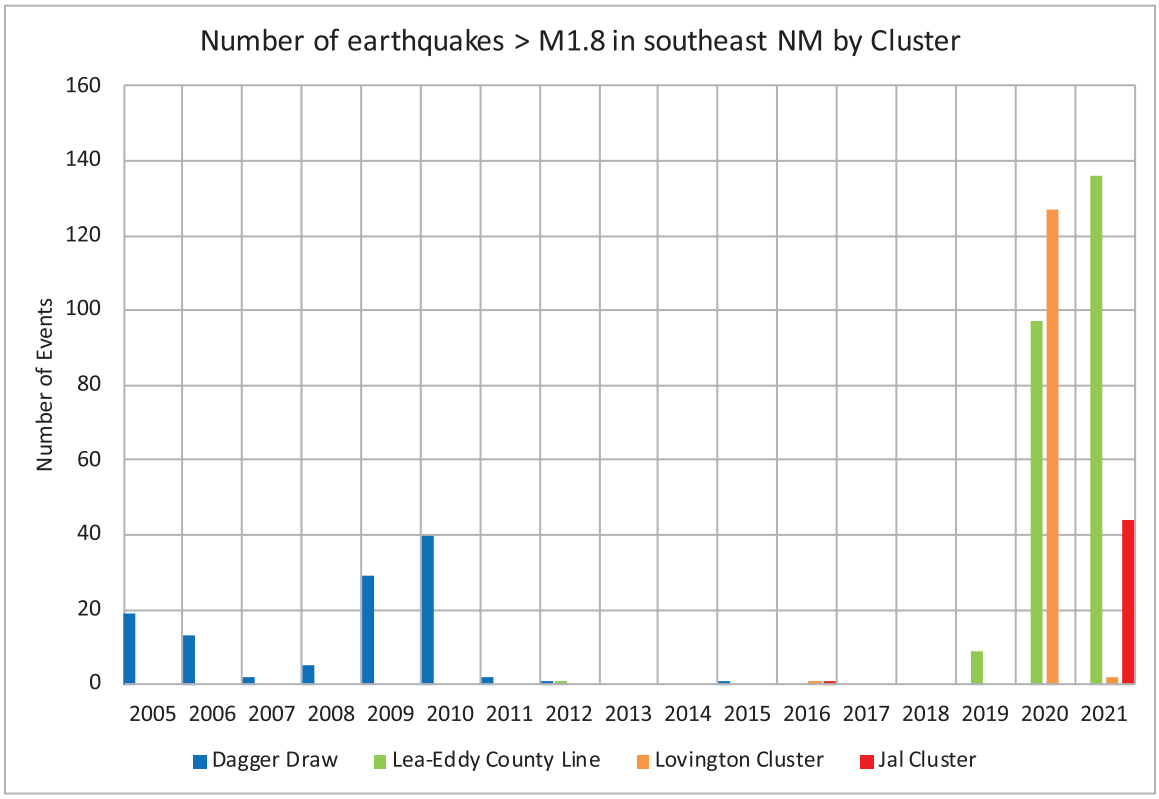


Figure 4. Number of earthquakes larger than M 1.8 detected in each of four major clusters in southeastern New Mexico by the New Mexico Tech Seismological Observatory between 2005 and 2021. Blue bars represent earthquakes in the Dagger Draw cluster, which was active primarily prior to 2010. Green bars represent the Lea-Eddy county line cluster, which began activity in 2019 and has increased in activity each year through 2021. Orange bars represent the Lovington cluster, which was active primarily over a 3 day period from 28 to 30 June 2020. Red bars represent the Jal cluster, which began activity in 2021 and continues to the present.

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Beginning around 2015, the number of earthquakes in the Delaware portion of the Permian Basin began to rise significantly above the baseline rate. This increase occurred in both the Texas and New Mexico portions of the basin, although the increase has not been as large in New Mexico as in Texas. The New Mexico Tech Seismological Observatory (NMTSO) located a total of 702 earthquakes in southeastern New Mexico larger than M 1.8 between 2005 and 2021 (Figs. 1 and 3). We consider only events larger than M 1.8 because that is the estimated magnitude of completeness of the network. Before 2020, the largest number of events recorded in a single year was 43 in 2010, primarily due to seismicity associated with the Dagger Draw oil field. Between 2011 and 2018, the largest number of M 1.8 or larger events recorded in a single year in southeastern New Mexico was seven, reflecting an ongoing but very low level of induced seismicity. However, in 2019, that rose to 26, and in 2020, 271 earthquakes larger than M 1.8 occurred in southeastern New Mexico. Nearly half of the events from 2020 occurred in a cluster of events over 3 days from 28 to 30 June 2020 between Lovington and Hobbs, New Mexico (Fig. 4). The largest event in the cluster was a M 3.0 event on 28 June, which occurred in an area that had seen little seismicity prior to this cluster. Four additional monitoring stations were installed in the area; since then, only low levels of seismicity have been observed.

In 2021, the total number of events larger than M 1.8 recorded by the NMTSO was 247. This was a drop from 2020, but, excluding the Lovington cluster, the overall amount of seismicity increased from 2020. The largest increase in seismic activity in southeastern New Mexico between 2018 and 2021 occurred along the southern border of New Mexico near the boundary between Lea and Eddy Counties (Fig. 4), where the two largest earthquakes since the decline of seismicity near Dagger Draw in 2011 were recorded: a M 3.4 event on 19 March 2021 and a M 4.0 event on 19 July 2021. After these events, saltwater disposal rates in this area declined, and the amount of seismicity in this cluster also declined in the last 3 months of 2021. Rates of seismicity in other parts of southeastern New Mexico continued to rise through the end of 2021, including an ongoing cluster of activity near Jal, New Mexico (Fig. 4), that began in 2021 and has continued into early 2022.

Raton Basin

Induced seismicity was first observed in the Raton Basin of New Mexico and Colorado beginning in 2001. Although this area experienced some seismicity prior to the advent of coalbed methane production in the region, the rate of seismicity significantly increased soon after production started. Between 1970 and 2000, only one earthquake larger than M 4.0 was detected, while from 2001 to 2020, 15 earthquakes larger than M 4.0 were recorded in the basin (Rubinstein et al., 2014). The largest overall recorded earthquake was a M 5.3 earthquake near Trinidad, Colorado, in 2011, while the largest earthquake in the New Mexico portion of the basin was a M 5.0 earthquake in 2005. Approximately 70% of the earthquakes recorded in the Raton Basin occurred in the New Mexico portion of the basin (Glasgow et al., 2021). The number and size of events in this basin have declined in recent years, although earthquake activity is still ongoing.

SEISMIC MONITORING IN NEW MEXICO

Seismic Monitoring in Socorro

The seismic monitoring program in New Mexico began at the New Mexico Institute of Mining and Technology in 1957 with the hiring of Dr. Allan R. Sanford, who established the first program of seismic monitoring in the state (Sanford et al., 2000). In 1960, a three-channel seismograph began intermittent operation ~5 km west of Socorro (station SNM). Seismometers in Socorro were used to establish the existence of the Socorro magma body based on reflected arrivals observed in the seismograms (Sanford and Long, 1965). In 1969, station SRM was added ~30 km north of Socorro. In 1982, a network of eight permanent telemetered stations was established around Socorro. This network, the NMTSO, continues to the present, although some stations have been discontinued and others added. Most of the stations are single-component short-period stations, except for Y22A, which began operation as part of the Transportable Array in 2008 and was later adopted by the NMTSO, and Y22D on the campus of the Incorporated Research Institutions for Seismology (IRIS) Portable Array Seismic Studies of the Continental Lithosphere (PASSCAL) Instrument Center.

Preliminary Seismic Monitoring in the Permian Basin

In 1974, following the initial seismic investigation of the proposed WIPP site, a permanent recording seismograph was installed at the location of the proposed site. After the installation of this station, 159 earthquakes were located between 1974 and 1979 (Sanford et al., 1980). In 1979, the U.S. Congress authorized the WIPP site for nuclear waste disposal, and by 1992, seven stations were operating in southeastern New Mexico for the purpose of monitoring seismicity in the vicinity of the WIPP site, all of which are still operating today as part of the NMTSO. These seven stations recorded a generally diffuse pattern of seismicity throughout the region, with a concentration of activity in the area of the Central Basin Platform (Sanford et al., 2002). In 1999, the first shipments of nuclear waste were received by WIPP, and the NMTSO continued to monitor the area for seismicity. In 2004 and 2006, two additional stations were added to the network near the Dagger Draw oil field due to the increase in seismicity in that area. In 2015, the network was upgraded from radio telemetry to digital recording transmitted by cellular modem. However, at the time, all stations were still single-component, short-period stations since seismicity was relatively low.

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Current Seismic Monitoring in Southeast New Mexico

The increase in seismicity in the mid-2010s in both the Texas and New Mexico portions of the Permian Basin drove a renewed concern about seismicity in the area. The state of Texas established TexNet, which began providing information about earthquakes in Texas in January 2017 (Savvaidis et al., 2019). To improve its network coverage, the NMTSO cooperated with TexNet to collocate three TexNet broadband stations at sites with NMTSO stations to improve data quality in the area. In addition, a donation of six broadband seismometers in 2020 allowed the NMTSO to expand the network by two additional stations and convert four others to broadband recording. These improvements have improved the quality of data collected by the network, allowing for more scientific studies focused toward understanding the causes of induced seismicity in the region.

The current NMTSO seismic monitoring network in southeastern New Mexico consists of 15 stations: five single-component short-period stations and 10 three-component broadband stations (however, two of these stations do not currently have real-time data collection). In addition, the USGS has installed a temporary network of 14 broadband stations in the New Mexico portion of the Permian Basin, for a total of 24 stations. Several private arrays are operated by the oil and gas industry in the area, though data from these networks are not routinely available to the NMTSO for analyses.

Raton Basin

In 2016, seven broadband seismic stations were installed in the Raton Basin by the University of New Mexico (UNM) to monitor induced seismicity. Prior to that, only one permanent station was located in the Raton Basin, station T25A, on the eastern edge of the basin (Wang et al., 2020). Additionally, UNM installed an array of 96 nodes for several months in 2018. The improved station coverage of the basin has made possible techniques to relocate events to better understand the fault structure of the basin.

San Juan Basin

In contrast to the Permian Basin, the San Juan Basin has had extremely limited seismic monitoring throughout its history. Aside from the period between 2008 and 2010, when the Transportable Array was passing through, no broadband seismic monitoring stations have been installed within the New Mexico portion of the San Juan Basin, although one station lies along its northern boundary in Colorado. This lack of coverage significantly hinders detection of small earthquakes that may be occurring in the area (earthquakes of M 3.0 or larger would still likely be detectable). Although the San Juan Basin experiences significantly less fluid injection than the Permian Basin in New Mexico, and it is therefore at significantly less risk of induced seismicity, interest in the region for potential carbon sequestration projects has increased in the past several years. The NMTSO recently installed three temporary stations in the San Juan Basin to boost coverage in this area; however, installation of a permanent network will be necessary in the future to monitor potential induced seismicity in the region.

Other Seismic Networks

Several other networks have also operated in New Mexico at various times. For example, in 1973, the Los Alamos National Laboratory installed a network of more than 20 single-component, short-period seismometers near Los Alamos, New Mexico (House and Roberts, 2020). It was originally designed for research into monitoring for nuclear weapons detonations, but it has also been used to monitor local seismicity. Although the network configuration has changed over time, it has continued to operate to the present day. Unfortunately, the data from this network are not publicly available in real time. As part of the Global Seismic Network (GSN), station ANMO operates in Albuquerque, New Mexico, the home of the Albuquerque Seismological Laboratory, which is responsible for maintenance of the GSN. Because of this, at times, additional stations are deployed in the area for testing purposes.

In addition to these permanent seismic networks, numerous temporary deployments have enhanced seismic monitoring in New Mexico. The Transportable Array, which operated in New Mexico from 2008 to 2010, provided coverage throughout the state. The SIEDCAR network operated in southeastern New Mexico at the same time as the Transportable Array. Data from it were used to relocate Dagger Draw events.

Efforts to locate earthquakes in New Mexico have also made use of networks from bordering states, particularly TexNet in Texas, the Colorado Geological Survey Seismic Network, and the Arizona Broadband Seismic Network, as well as stations operated by the USGS in those states.

CONTINUING EFFORTS

The additional stations recently installed in southeastern New Mexico have significantly improved our ability to detect induced seismicity; however, there are signs that further improvements to the network may be needed. As more events are recorded outside the area of the network, such as the swarm in Hobbs and additional events to the west of Carlsbad, it will be important to consider adding stations to improve the spatial coverage of the network, as well as densifying the network in areas of particular interest. The NMTSO is also working to improve its data-processing capabilities. In the past, the lack of broadband stations in the region limited the information that could be obtained about each event. The additional data from the new broadband stations allow event depths to be calculated more precisely, velocity models to be developed for the region (Huang et al., 2019), and local magnitudes to be calculated using properties specific to the region (Kavoura et al., 2020).

Data collected by the NMTSO are essential for scientific assessments and regulatory responses to induced seismicity in

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New Mexico. For example, in 2021, the New Mexico Oil Conservation Division developed a seismicity response protocol to require heightened monitoring and possible injection rate reductions when either two M 2.5 events or one M 3.0 event occurred within a certain distance of a saltwater disposal well. Therefore, it is imperative to provide quick, accurate information to guide these regulatory responses. The NMTSO has created an improved website to disseminate information and is working to process data more quickly, so that the network can provide event information in near real-time.

In addition to improving data-collection and data-processing methods going forward, the NMTSO is working to preserve and reanalyze older data collected by the network. An understanding of the early history of seismicity in the Permian Basin is valuable to understand how seismicity has changed over time as oil and gas production in the region has evolved. Because TexNet, which monitors the Texas portion of the Permian Basin, only began operation in 2017, integration of data sets from different regional networks operating in the region is essential to best understand the earlier seismicity. Data sources from this time period include the NMTSO, the Lajitas TXAR seismic array (Frohlich et al., 2020), permanent USGS stations, and temporary seismic networks including the Transportable Array from 2008 to 2010. Since the earliest seismic records collected by the NMTSO in the Permian Basin date back to the 1970s, data preservation remains a challenge. The NMTSO began collecting digital records of data in 2002; prior to that year, all seismic records were collected on paper. Efforts will need to be undertaken to preserve and digitize these older data to ensure they are not lost.

SUMMARY

New Mexico experiences relatively fewer induced seismic events than its neighbors in Texas and Oklahoma, but significant induced seismicity has occurred in the Raton and Permian Basins, and seismicity in the Permian Basin has increased significantly between 2015 and 2021, with a tenfold increase in the number of recorded events with at least M 1.8 between 2015 and 2021. Due to the state's history of naturally occurring seismicity and interest in the WIPP site in southeastern New Mexico, there is a long record of seismicity throughout much of the state that can provide insights about the ways in which induced seismicity has changed over time. Recent efforts have significantly expanded that network and introduced collaboration with neighboring states and federal agencies to better understand the causes of induced seismicity in the region. More work is needed to take full advantage of the available data to provide a practical understanding of induced seismicity to regulators, industry, and the public.

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