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Two-year survey of earthquakes and injection/production wells in the Eagle Ford Shale, Texas, prior to the M_W4.8 20 October 2011 earthquake

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ABSTRACT

Between November 2009 and September 2011 the EarthScope USArray program deployed ∼25 temporary seismograph stations on a 70-km grid in south-central Texas between 27°N–31°N and 96°W–101°W. This area includes the Eagle Ford Shale. For decades this geographic region has produced gas and oil from other strata using conventional methods, but recent developments in hydrofracturing technology has allowed extensive development of natural gas resources from within the Eagle Ford. Our study surveys small-magnitude seismic events and evaluates their correlation with fluid extraction and injection in the Eagle Ford, identifying and locating 62 probable earthquakes, including 58 not reported by the U.S. Geological Survey. The 62 probable earthquakes occur singly or in clusters at 14 foci; of these foci, two were situated near wells injecting recently increased volumes of water; eight were situated near wells extracting recently increased volumes of oil and/or water; and four were not situated near wells reporting significant injection/extraction increases. Thus in this region, while the majority of small earthquakes may be triggered/induced by human activity, they are more often associated with fluid extraction than with injection. We also investigated the M_W4.8 20 October 2011 Fashing earthquake—the largest historically reported earthquake in south-central Texas—that occurred two weeks after the removal of the temporary USArray stations. A field study indicated that the highest-intensity (MMI VI) region was about 10 km south of 2010–2011 foreshock activity, and that there were no high-volume injection wells within 20 km of the MMI V–VI region or the foreshocks. However, the 20 October 2011 earthquake did coincide with a significant increase in oil/water extraction volumes at wells within the MMI V–VI region, and this was also true for previous earthquakes felt at Fashing in 1973 and 1983. In contrast, our study found significant increases in injection prior to an m_{bLG}3.6 20 July 1991 earthquake near Falls City, Texas. Thus the Eagle Ford geographic region, with seismic activity associated both with extraction and injection, appears to be more complex than the Barnett Shale of northeast Texas, where a similar survey found possible correlations only with fluid injection.

1. Introduction

While earthquake seismologists have long recognized that fluid injection into the subsurface sometimes triggers earthquakes (Healy et al., 1968; Hsieh and Bredehoeft, 1981; Nicholson and Wesson, 1990; Suckale, 2009), this phenomenon has gained attention recently (e.g., National Research Council, 2012; Ellsworth, 2013) because earthquakes near injection disposal wells have occurred in several locations where no previous seismicity had been reported historically. These include Dallas–Fort Worth, TX (Frohlich et al., 2011; Janska and Eisner, 2012; Reiter et al., 2012), Cleburne, TX (Howe, 2012), Timpson, TX, and Youngstown, OH. In these cases the injected fluids were generated by shale-gas development projects where wells are hydrofractured to enhance subsurface permeability. The production of gas is accompanied by the flowback of hydrofracture fluids that require disposal, typically accomplished by injecting them elsewhere in designated Class II disposal wells.

This study investigates the relationship between seismicity, fluid injection, and fluid extraction in the Eagle Ford region of south-central Texas (Fig. 1). Gas and oil have been produced extensively from this region since before 1950, mostly from the Edwards formation, a Lower Cretaceous limestone that underlies the Upper Cretaceous Eagle Ford Shale. A series of southwest–northeast fault

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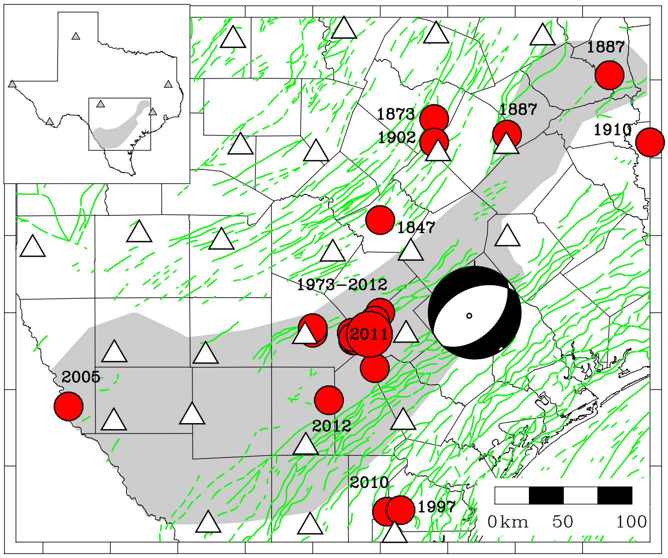

Fig. 1. Map showing extent of Eagle Ford Shale (shaded gray), USArray temporary seismograph stations operating during Nov 2009 to Sept 2011 period (triangles), historical seismicity (red circles; from Frohlich and Davis, 2002; and the NEIC), and mapped faults (green; from Ewing, 1990). Large red circle labeled "2011" is NEIC location for the 20 October 2011 M_W4.8 earthquake, and beachball at right is focal mechanism determined by the St. Louis group (Herrmann et al., 2011). Other labels indicate year of historical earthquakes. Inset with boundary of Texas shows mapped area and broadband seismograph stations (gray triangles) operating in 2005 prior to passage of the USArray. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

systems (see Fig. 1), including the Fashing Fault Zone, cuts through much of the Eagle Ford region (Harbor, 2011). Most of these fault systems formed in the proximity of up-dip Triassic/Jurassic salt and result from basinward salt movement (Montgomery, 1990). In some regional fields these faults provide the trap that makes petroleum production viable.

Earthquakes with epicenters within or on the boundaries of producing fields have occurred since a tremor was reported by residents of Fashing, TX, on 25 December 1973 (e.g., Pennington et al., 1986; Olson and Frohlich, 1992; Davis et al., 1995; Frohlich and Davis, 2002). The largest of these earthquakes, with M_W4.8, occurred on 20 October 2011 near the Fashing Gas Field. Since 2008 the Eagle Ford has been an intense focus of shale-gas development involving extensive hydrofracturing; this raises two questions: (1) Are small earthquakes within the Eagle Ford region associated either with fluid extraction or injection? And (2) Does the evidence indicate the M_W4.8 20 October 2011 earthquake is of natural origin, triggered by fluid extraction, or triggered by the injection to dispose of flowback brines associated with production and hydrofracturing?

Only a handful of seismograph stations operated in south-central Texas prior to 2009 (Fig. 1); however, the passage of the EarthScope USArray transportable array between 2009 and 2011 provided an unprecedented opportunity to identify and accurately locate earthquakes. The present study will survey seismic activity during this period and evaluate its relationship to both injection and extraction wells. We will compare results from the Eagle Ford region to results from a companion study of the Barnett Shale (Frohlich, 2012). We also present a summary of felt reports for the 20 October 2011 Fashing earthquake.

The present survey searches for possible correlations between seismicity and extraction/injection rates in the Eagle Ford region. Interpreting the significance of these correlations will require a more thorough analysis of local geology as well as physical modeling of subsurface hydrological/stress. This is the focus of an ongoing companion study for which we hope to enlist industry cooperation concerning the details of subsurface structure.

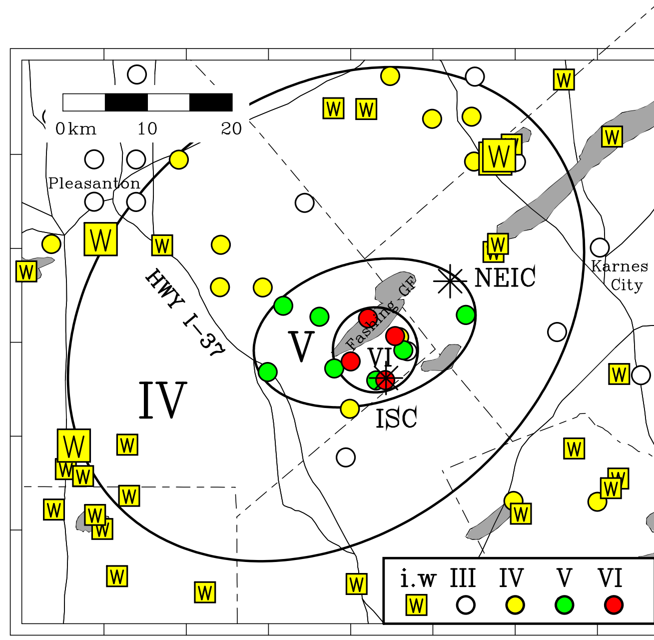

Fig. 2. Map of locations of felt reports (circles) defining the boundaries of regions experiencing modified Mercalli intensity (MMI) IV, V, and VI during the 20 October 2011 earthquake (see also Table S2 and Fig. S2). Yellow squares labeled "W" are injection wells: larger symbols—wells with maximum monthly rates >100,000 BWPM (16,000 m^3/mo); smaller symbols—wells with maximum monthly rates >10,000 BWPM (1600 m^3/mo). Stars '∗' indicate 20 October 2011 epicenter as reported by the NEIC and ISC. Shaded gray regions are producing oil and gas fields from Galloway et al. (1983) and Kosters et al. (1989). Note that there are no injection wells within ∼20 km of center of MMI VI area. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Data and methods

2.1. Felt reports for the 20 October 2011 Fashing earthquake

We gathered felt report information (Fig. S2 and Fig. 2) in two ways. Following the 20 October 2011 earthquake one of the authors (M.B.) spent three days in the epicentral region interviewing residents, concentrating his efforts in the higher-intensity areas. We augmented these data with "Did you feel it?" (DYFI) information provided by the National Earthquake Information Center (NEIC). The DYFI program (Atkinson and Wald, 2007; Wald et al., 2011) is an Internet-based program where individuals can provide unsolicited responses to questions about their experiences and location during an earthquake. The responses are assigned a modified Mercalli intensity (MMI) value; the NEIC routinely presents summary online maps of the MMI distributions. For this study the DYFI data were especially useful for establishing boundaries for the MMI III and MMI IV regions, whereas the in-person interviews constrained the MMI V and MMI VI boundaries that had smaller areal extents but were situated in regions where population was sparse.

2.2. Seismic data and earthquake location

Our procedure for identifying seismic events involved three steps. The first step was to acquire vertical-component seismograms for the ∼25 USArray stations operating in the study area between November 2009 and September 2011. Then, to identify time intervals when locatable seismic events might have occurred,