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New View of North Texas Earthquakes

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ABSTRACT

North Texas started experiencing earthquakes in 2008, which increased in magnitude and frequency from 2011 through mid–2015. Wastewater injection through salt water disposal wells has been tied to inducing these earthquakes. Injection has continued to present day; however, the earthquake occurrence has nearly stopped since mid–2015. Seismologists struggle to explain why earthquakes are associated with some faults and not others in the region. They have focused mainly on the pore-pressure component on induced earthquakes. A recent paper suggests that there is a fluid component that appears to impact the frequency, magnitude, and location of the induced earthquakes. However, millions of gallons of wastewater are being injected in the Fort Worth Basin (FWB) of Texas.

The theory presented here has to do with the structures at the Ordovician Ellenburger Formation level and underlying top of basement level. They outcrop northwest of Austin in Central Texas and structurally dip to the northeast with the deepest point located under the Dallas–Fort Worth (DFW) area. The faults associated with the larger magnitude earthquakes are located where the Ellenburger is near and at its deepest point. Within the Ellenburger, the highest formation pressures are under the DFW area. Here the Ellenburger Formation pressure is also enhanced by the wastewater being injected. Injected fluids will flow from high pressure to lower pressure zones. The injected fluid migration from NE to SW, in an updip direction, provides the lubrication to those structurally updip faults and could explain the lack of seismicity at those faults. The high fault-slip potential faults of the DFW/Venus area are not lubricated by the injected fluids and subject to environmental conditions that appear to impact earthquake frequency and magnitude. By adding a fluid component to the analysis, a better understanding of the timing and pattern of earthquakes is possible and could be relevant to current hydraulic fracturing practices.

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INTRODUCTION

Until 2008, North Texas has historically been absent of earthquake activity (Frohlich et al., 2016). Horizontal drilling and hydraulic fracturing have helped overcome the poor porosity and permeability of the Barnett Shale gas production in North Texas. This process uses a large volume of water, which is recovered when the well is put on production. This water is known as frack flow back water. Normal hydrocarbon production includes salt water that is in the formation with the oil and gas. This salt water is combined with any frack flow back water and disposed through special wells drilled to inject this wastewater into a deep non-productive formation. These wells are known as salt water disposal (SWD) wells. Many of these SWD wells are located throughout the counties that are part of the Fort Worth Basin (FWB) (Fig. 1). In the FWB, wastewater is injected into the Ordovician Ellenburger Formation.

Since the 1960s, seismologists have tied the increased subsurface pressure generated by injecting wastewater to inducing earthquakes. Since earthquakes began in 2008, 35 magnitude 3 (M3) and larger earthquakes have occurred in the FWB through January 2020 (Fig. 1). As re-

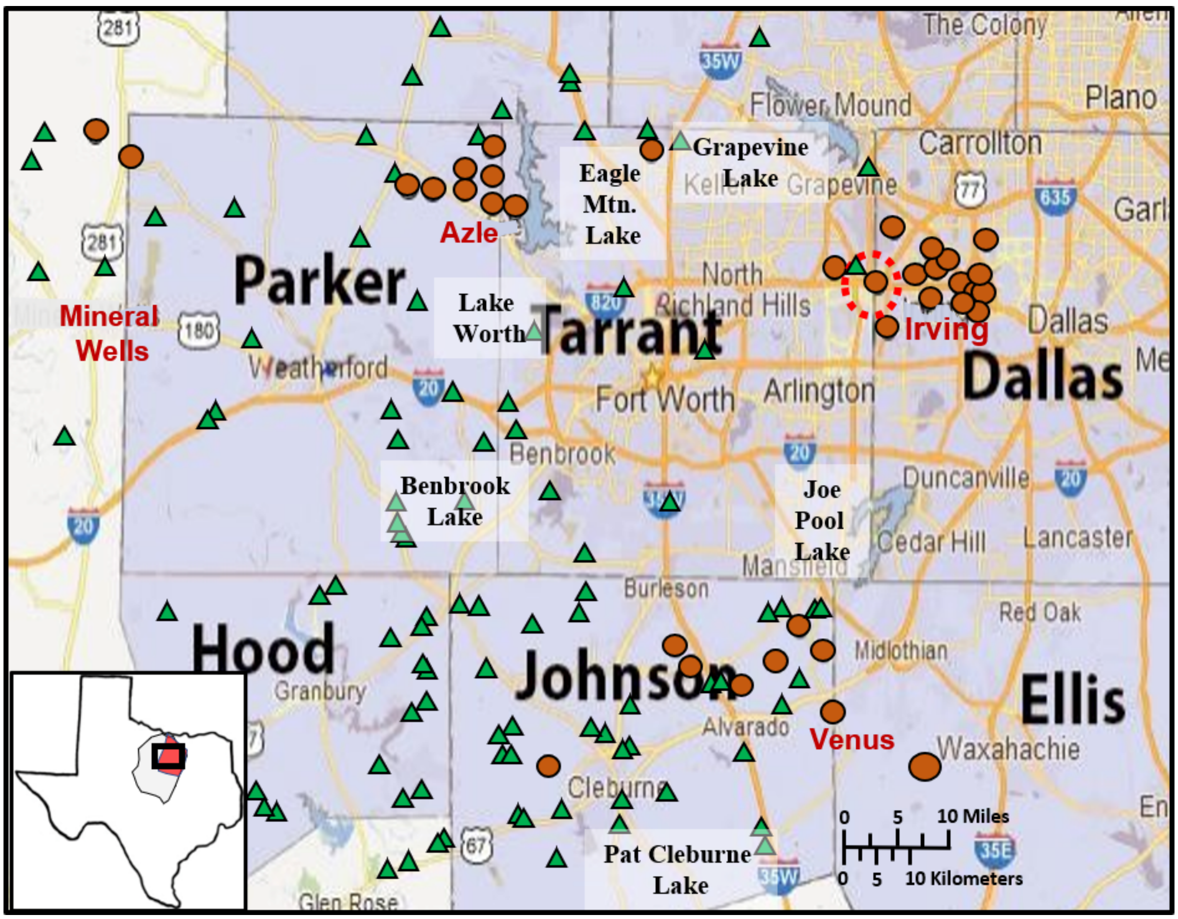

Figure 1. Location map of 35 M3 and larger earthquakes in the Dallas-Fort Worth area from January 2008 to January 2020 (solid red circles). Red dash circle is location of first FWB earthquake. Earthquakes are focused in four counties, Parker, Tarrant, Dallas and Johnson. The largest number of earthquakes occurs in Dallas County. SWD well locations are green triangles. Referenced DFW area lakes are labeled.

searchers began studying these earthquakes, seismographs (temporary and permanent) were established near the earthquake active sites. This allowed many studies to tie the earthquakes to faults located near the SWD wells (Frohlich et al., 2016; Hornbach et al., 2016; Magnani et al., 2017; Quinones et al., 2019; and Hennings et al., 2019). These studies also identified many other faults near SWD wells that did not have any associated earthquakes. Until now there has not been an explanation for why earthquakes are occurring on some faults and not others. A recent study (Rader, 2019) matched the North Texas earthquake pattern for M3 and larger earthquakes to the environmental conditions around the Dallas–Fort Worth (DFW) area. Large magnitude earthquakes were occurring during drought periods and stopping during wet periods using lake levels within the FWB area (Fig. 1) as a measure of drought. The proposal suggested that the environmental conditions during wet periods lubricated the fault surface reducing the frictional strength of the fault and allowing the fault failure to occur at lower energy levels generating low magnitude earthquakes. When the area experienced a drought, less water was available to lubricate the fault causing it to lock up, requiring more energy for the fault to fail. The larger energy released during failure under drought conditions resulted in larger magnitude earthquakes.

The magnitude and frequency of earthquakes increased as the drought in North Texas continued from 2012 to early 2015. In late May 2015, a heavy rain and flood in the Dallas area correlated with the reduction of earthquake activity in the FWB. This paper introduces a fluid factor that is tied to the earlier study (Rader, 2019) and could also explain why some faults do not have earthquake activity even when located near SWD wells.

METHODS

Southern Methodist University (SMU) and the University of Texas at Austin (UT) have generated an earthquake catalog for the North Texas area. Overlay of the catalog earthquake data from (Quinones et al., 2019) for M2 to M4 earthquakes over extended lake level data used by Rader (2019) reveals a pattern of lake level changes to the frequency and magnitude of the recorded earthquakes (Fig. 2). The North Texas drought period from 2012 to 2015 indicates that as the drought increased the number, frequency, and magnitude of earthquakes also increased (Rader, 2019). Lake levels are only used as a measure of the fluid contained in the environment of the faults and as a measure of the drought. When the lake fill levels are above 90% fill (solid red arrows, Fig. 2) there are few to no earthquake events. There are many incidences where lake levels increase during a drought period (dashed purple arrows, Fig. 2) and the same time period there is a reduction of earthquake magnitude and frequency. There is an observed decrease in occurrences of even low magnitude (M2 to M3) during an increase in lake levels. This pattern cannot be explained strictly by pore-pressure changes caused by changes in the injection volumes from SWD wells. A possible theory, presented by Rader (2019) and supported by this paper, suggests lubrication of fault surfaces reduces the frictional strength of the fault. Less energy is then needed for the fault to fail and generates smaller magnitude earthquakes. If less fluid is present (during a drought), more energy is required for the fault to fail generating larger earthquakes. This adds a fluid component to pore-pressure as factors impacting earthquake magnitude, location, and frequency. Lubrication is a good theory, but SWD wells are injecting large volumes of fluid into the subsurface formation.

The theory presented here has to do with the structures at the Ellenburger Formation level and underlying top of basement level (Fig. 3). The Ellenburger and basement outcrop northwest of Austin in Central Texas and explain that the Ellenburger Formation is not a closed system, where SWD injection would continue to build pressure in the formation. The Ellenburger Formation structurally dips to the northeast with the deepest point located under the DFW area. The faults associated with the larger magnitude earthquakes are also located where the Ellenburger is near and at its deepest point (Fig. 3). Hennings et al.'s (2019) fault analysis on the faults in the Central and North Texas area highlights many faults that are oriented to the maximum stress field and have the greatest fault-slip potential. The faults with a high fault-slip potential in the DFW area appear to be associated with the earthquake activity (Fig. 3). Other high fault-slip potential faults in the southern FWB area do not have the same high magnitude

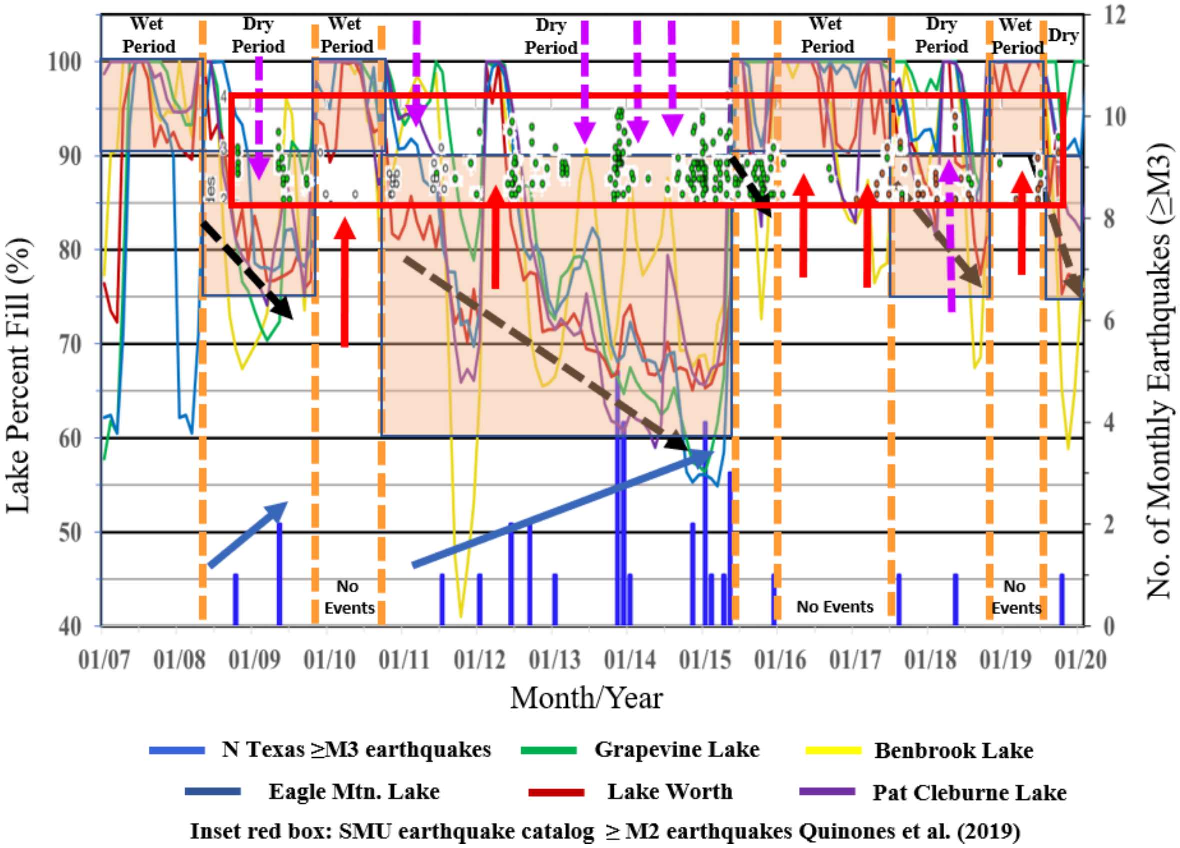

Figure 2. North Texas earthquakes and area lakes percent fill (%). Curves for the five area lakes, Benbrook (Yellow), Grapevine (green), Lake Worth (brown), Eagle Mountain (blue), and Pat Cleburne (purple). Joe Pool Lake is not included because the water level is managed by the U.S. Army Corp of Engineers to provide a source of drinking water to nearby cities. Blue bars represent the number of earthquakes occurring by months. Dry/drought periods are labeled for times of lowering lake levels (decreasing fill/ black dashed arrows). Wet periods are when lake levels are near or at 100% fill (red solid arrows). Positive lake level changes (purple dashes arrows). Red insert box has earthquakes from North Teas earthquakes catalog (Quinones et al., 2019) for M2 to M4 with M3 align to the 90% lake fill line.

earthquakes despite their proximity to a large number of SWD wells. So how does this all fit with the water lubricating faults and the North Texas earthquake pattern?

RESULTS

The key factor applied here is that fluid will flow from high pressure to lower pressure zones. Within the Ellenburger, the highest formation pressures are under the DFW area where the Ellenburger is at its deepest burial (Fig. 3), where the formation pressure is also enhanced by the fluid being injected into the Ellenburger Formation, and this pore-pressure increase is the factor seismologists have tied to inducing the earthquakes. The SWD well fluid injected into the Ellen-

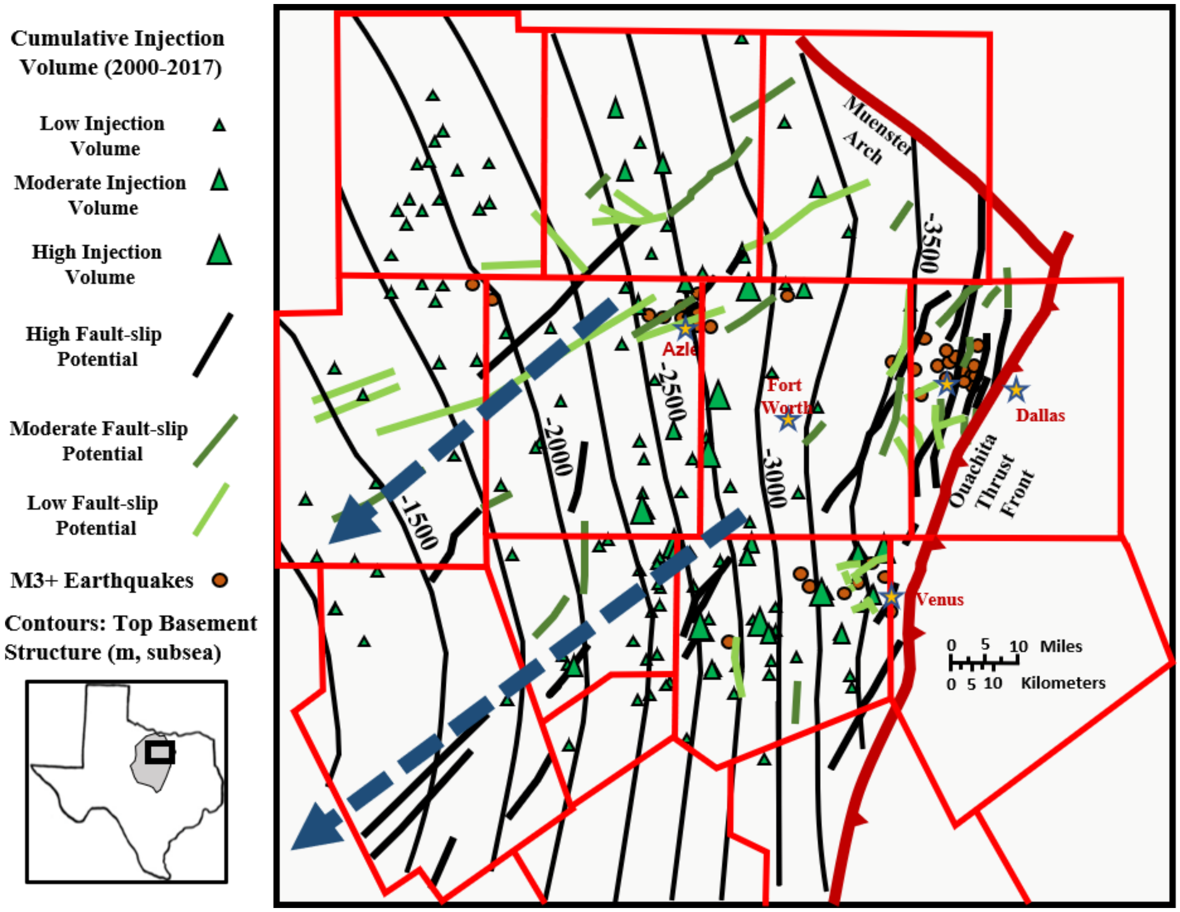

Figure 3. Top of basement in FWB (contourrs in meters subsea elevation) with SWD well volumes (green triangles) and fault slip potential faults (Hennings et al., 2019). Basement is deepest beneath DFW area where the Ellenburger Formation has the greatest formation pressure. The blue dash arrows indicate the SWD fluid migration from NE to SW (high pressure to lower pressure).

burger Formation migrates updip, flowing from this high pressure to the southwest towards central Texas where the formation outcrops (dashed blue arrows, Fig. 3). The seismically active faults are located downdip from the majority of the SWD wells and fluid being injected (Figs. 3 and 4). The high fault-slip potential faults in the southern portion of the FWB are in the SWD fluid migration path and are updip from the seismically active faults. The injected fluid provides the lubrication to those updip faults and could explain the lack of seismicity at those faults. The majority of the SWD wells in the FWB are located south and west of the DFW area. Beneath DFW, the high formation pressure prevents the injected fluids from lubricating these structurally low faults. Without access to the injected fluid, these faults can only be lubricated by surface water events. Hennings et al. (2019) and Quinones et al. (2019) plotted the focal depth of the North Texas earthquakes on cross-sections through the FWB. Several earthquake focal depths occur above where Magnani et al. (2017) has indicated that the faults terminate. This indicates that the faults do propagate into the shallow section where they can have access to the surface environmental conditions.

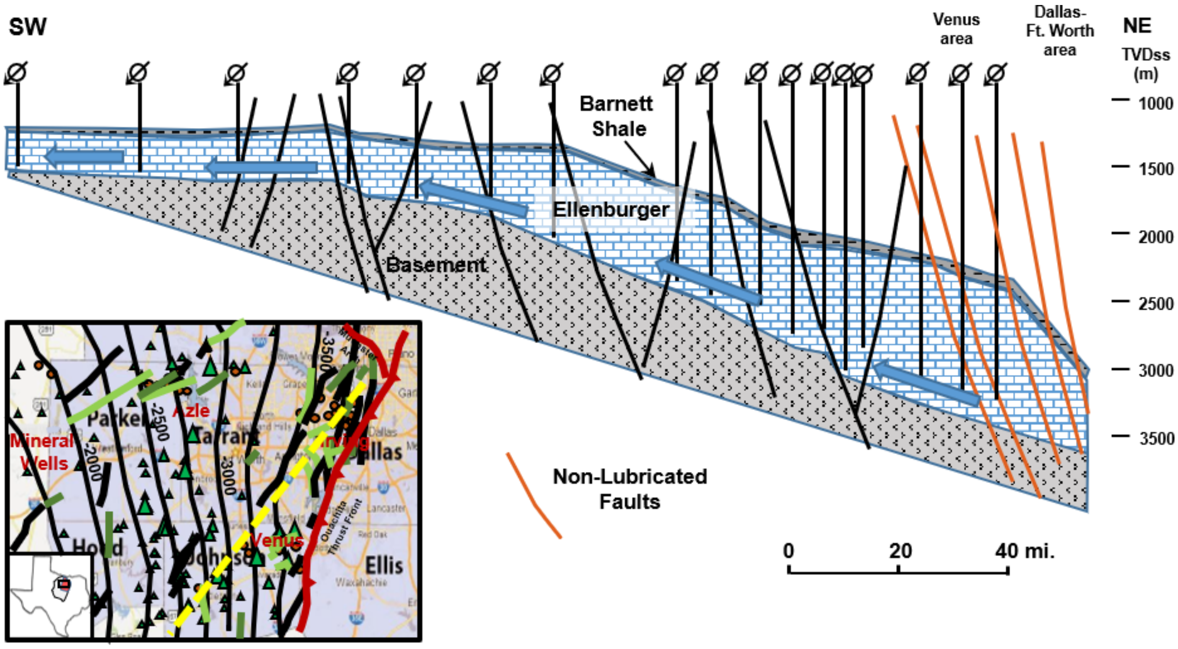

Figure 4. NE–SW schematic cross-section of injected fluid flow lubricating updip faults while seismically active faults are downdip of the SWD wells. The approximate location of the cross-section is the dashed yellow line in the map. SWD fluid migration direction is the blue arrows. Fluid flows from high pressure to low pressure. The Ellenburger Formation has the highest formation pressure under the DFW area where it is at its greatest depth. The lubricated faults do not have large magnitude earthquakes. The non-lubricated faults below the DFW area are subjected to environmental conditions and are lubricated by the local rainfall.

Recently, hydraulic fracturing induced earthquakes are of concern for many people. The hydraulic fracturing conducted in South and West Texas has associated induced seismicity. If a fluid component is considered, the low rainfall in these parts of Texas could explain why the pore-pressure increase from the hydraulic fracturing process would generate earthquakes on critically stressed faults. The dry conditions lock up the nearby faults requiring a larger amount of energy before fault failure, thus generating larger earthquakes. This theory suggests that hydraulic fracturing be done during wet/non-drought periods to reduce the occurrence of large magnitude earthquakes.

CONCLUSIONS

The seismicity in the North Texas FWB area has uncovered a correlation that appears to match earthquake activity of M3 and larger earthquakes to environmental conditions (Rader, 2019). Despite SWD wells injecting large volumes of fluid into the subsurface Ellenburger Formation, a theory of fault lubrication is possible. The Ellenburger Formation is at its deepest structural depth beneath the DFW area, a location that would have the highest natural Ellenburger Formation pressure. This natural pressure is enhanced by the pressure increase from the SWD injected fluids. Because fluids flow from high pressure to lower pressure zones, any SWD fluids will tend to migrate away from this high pressure. Only the high fault-slip potential faults in the FWB area that have associated large magnitude earthquakes are located in the northern FWB area. The high fault-slip potential faults to the south and west, updip of the DFW/Venus area, are lubricated by the injected fluids that migrate updip away from the high pressure. This would now explain the seismicity of the faults to the north and lack of seismicity for the high fault-slip potential faults located near SWD wells in the southern FWB.

Because the injection of wastewater alters the subsurface pore-pressure, which induces earthquakes, seismologists have only used pore-pressure to analyze induced seismicity. By adding a fluid component to the analysis, a better understanding of the timing and pattern of earthquakes is possible. Study of the structure of the injection formation could also lead to areas not lubricated by the injected fluid and define areas where earthquakes might occur. An understanding of the fluid component could be relevant to current hydraulic fracturing practices. It may be beneficial to conduct these processes during wet periods to allow any nearby faults; that might be impacted by the increased pressure; to fail at a lower stress level.

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