Evidence for subterranean deflagration to detonation transition induced seismic events near saltwater disposal wells in Oklahoma

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Abstract

Over the past 5 years, parts of Oklahoma have experienced significant increases in the number of small to moderate-sized earthquakes. A recent study [1] showed that in three areas that encompass the vast majority of the recent seismicity, the increases in seismicity follow significant increases in the rates of saltwater disposal into wells. This paper looks at specific saltwater disposal well and seismic locations, well design parameters and environmental influences that support a new hypothesis that many of the increased seismic events in Oklahoma over the past 5 years are due to subterranean deflagration to detonation transition (DDT) events of hydrocarbons within the Earth and not initiated by just slippage of existing "lubricated" fault lines.

Introduction

Deflagration to detonation transition (DDT) events [2] refers to a phenomenon in ignitable mixtures of A) a flammable gas and B) an oxidizer such as air (or oxygen) or chloride ions [3], when a sudden transition takes place from a subsonic deflagration rate of combustion to a supersonic detonation rate of combustion. Deflagration of flammable gasses can be initiated by C) an ignition source such as electrical current and/or electromagnetic radiation as well as D) an increase in pressure of the gas and resultant temperature increase above the autoignition temperature [4]. Within an enclosed space, deflagration events can build pressure and temperature and lead to sudden detonation. The effects of a detonation are usually devastating above ground and have adequate energy release to easily create seismic level events. The supersonic pressure wave front from the detonation does much of the damage.

Figure 1: June 26th, 2015 Natural Gas Explosion Measured 1.1 on the Richter scale [5] and most of the energy was likely directed above ground.

A propane (hydrocarbon) gas DDT event in Port Hudson, Louisiana in 1970 [6] produced the equivalent detonation of 50 tons of TNT or 31 tons of Nobel Blasting Powder, which is equivalent to a 4.3 Richter scale seismic event [7]. Hydrocarbons also have an autoignition temperature whereby the hydrocarbon will spontaneously ignite, the combustion rate can then continue until a potential detonation takes place.

Underground gasses are made up of a range of hydrocarbons, including methane, ethane and propane. We refer to the mixture of these natural hydrocarbons as “natural gas”. Natural gas is flammable in the 5% LEL -15% UEL by volume range [8] in a mixture with air. Richter scale level explosions of natural gas above ground are well known. It takes approx. six US pounds of methane in air detonating to produce the energy of a 2.5 Richter scale seismic event. At a depth of 10,000 feet, a 6 lb. pocket of natural gas in air at the 5% LEL under hydraulic pressure will only occupy approx. 0.9 ft3 of volume with a surrounding hydraulic pressure of 4300 psia. Natural gas can autoignite at 1163 degrees Fahrenheit with 0.29 mJ of energy for ignition [9]. Temperatures of the gas will increase under increased pressure. Actual underground pressure will vary with structural properties of the Earth and specific gravities of liquids in hydraulic communication with the gas, such as brine and the head pressure on the liquid such as from a hydraulic pump at the surface and friction losses.

Methane, the primary component of natural gas can also undergo oxidation chain reactions in the presence of chloride ions, a strong oxidant, which are exothermic and can lead to detonations if an ignition source, such as electromagnetic radiation is present and the gas is confined to a specific volume. Electrical potential above approximately 1.5V can induce electrolysis within a saltwater (NaCl) solution, separating Cl- ions and generating chlorine gas [10]. The US military has well established safety guidelines [11] for locating sources of electromagnetic radiation away from fuel sources such as natural gas storage. Storage tanks are also grounded to discharge any electrical potential to Earth. Radar and communication systems which operate at or above 225 MHz, and which are capable of mainbeam illumination of fuel-handling areas with a peak power density of 5 W/cm2 or greater, are deemed unsafe. Terrestrial sources of microwave radiation above 225 MHz includes sources of electromagnetic (EM) radiation such as radars, cell towers, microwave earth stations, microwave relay and TV towers. Natural sources of EM radiation include lightning, telluric currents and geomagnetic disturbances within the Earth and oceans.

Seismic activity has previously been linked with electromagnetic activity within the Earth and atmospheric conditions above. For instance in the March 2011 Japan earthquake, the atmosphere showed an increase in electron density and heating [12] for the two weeks leading up to the event. In January 2010, the DEMETER spacecraft showed a significant increase in ultra-low frequency radio signals before the magnitude 7 Haiti earthquake [13]. Electrical charge has also been detected within the Earth prior to Earthquakes and can be generated by rock formations under stress [14], [15]. Electromagnetic radiation induces electrical current in conductors through electromagnetic induction.

Seismic activity has also been linked with pressure pulsations in the atmosphere such as in the Great Alaska Earthquake of 1964 [16]. Atmospheric pressure pulsations were also detected before the Sumatra Earthquake [17]. These pulsations are very similar to those detected from an underground nuclear detonation or a DDT event pressure pulsation.

Gas odors have commonly been linked with earthquakes. For instance a witnesses of the New Madrid earthquakes in 1811 reported the strong smell of sulfur gasses[18], which are a naturally occurring contaminant of natural gas [19]. Sulfur smells have been very common during many earthquakes [20]. Oklahoma city residents have complained that sulfur odors have accompanied earthquakes in the area [21] and that residents can predict earthquakes based upon gas odor.

The surface location of a saltwater disposal (SWD) well is important as it needs to be an area where it is easily accessible by Operators who need to dispose of brine from their oil and gas production efforts [22]. Additionally, the geology beneath the surface is important. The first consideration is for a porous and permeable zone that is not considered an aquifer. A previously productive oil and gas zone that is now depleted and is porous and permeable is also suitable for brine disposal. Porous structures provide a good mixing region for liquids and gasses.

The Arbuckle region of Oklahoma is a preferred spot for SWD location due to the porous nature of the underground structure. Many disposal wells in Arbuckle region of Oklahoma are known as “gravity wells” [23] and are “under vacuum” meaning that the liquid level in the oil/gas tubing is normally below the ground surface level and can siphon brine into the well requiring lower pump horsepower for injection, which makes them more economical to use .

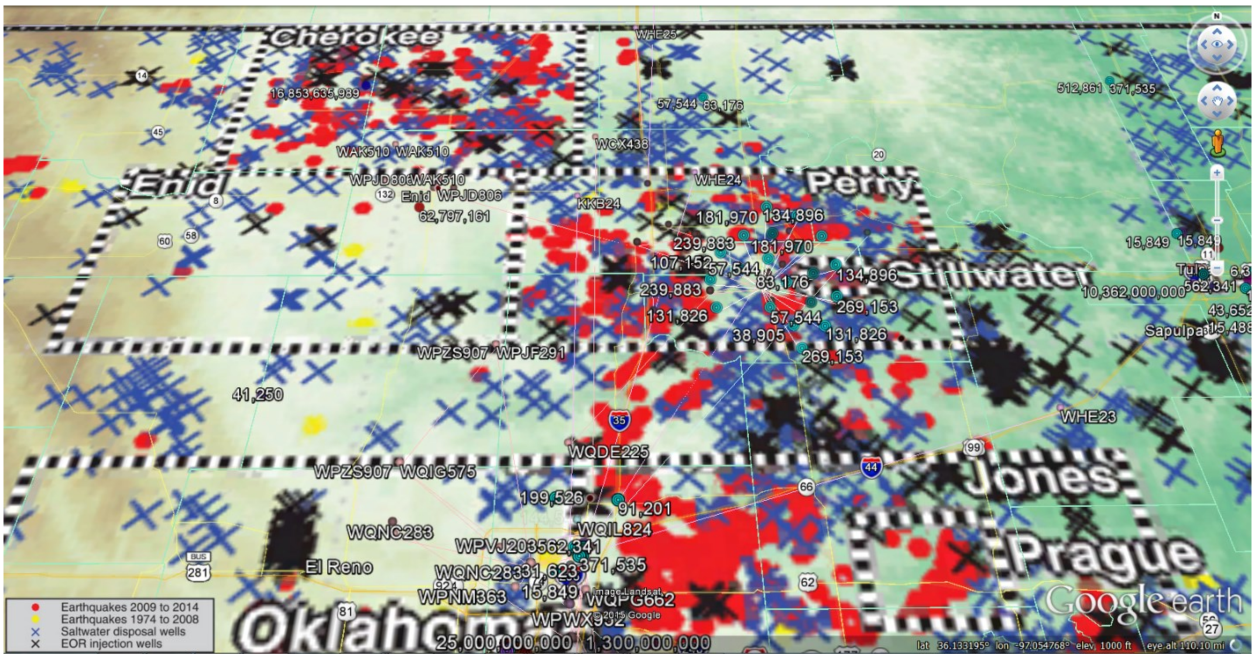

Figure 2: Oklahoma Earthquakes, Disposal Wells and sources of high gain EM Radiation. All values are EIRP peak watts of microwave radiation. Microwave relay towers show path of horizontal beam of radiation. Map Source [1]

In reviewing the SWD well design, the following operating parameters could increase the opportunities for a DDT event to present itself:

1. SWD well tubings and casings are typically small diameter piping. Using an example of 3” tubing and calculating the Froude number [26], any disposal rates above 650 barrels/day (~ 18.8 GPM) could potentially siphon/draw any air present in the piping into the SWD fluid that would be pulled down with the liquid and into the deep Earth below. In the case of the

Arbuckle wells, air could be present between disposal charges when the level in the pipe drops below the surface of the well. It would make sense that at higher disposal rates, higher air concentrations may make it into the deep formation below through the piping. The reference from this literature[29] shows an example of gravity SWD rates that exceed Froude numbers of 0.3 and can suck/siphon a lot of air deep into the earth, increasing the probability of a DDT event occurring due to air & natural gas mixing

"A single Arbuckle salt water disposal well in the Tobias Oil Field of eastern Rice County, for example, disposes brine pumped by 50 Arbuckle oil wells, most producing over 100 barrels of brine each, or over ***5,000 barrels of brine per day. [145 USGPM]*** *The well takes the brine by gravity flow through approximately* ***3500 feet of plastic-coated 5 1/2-inch casing used as tubing****. One can bear the roar of the falling water while standing many feet distant from the disposal well.* ***The energy input into such a salt water system is enormous****. Here, 50 large motor-driven pumps lift oil and brine from 3350 feet, then the separated brine flows horizontally in a gathering system, followed by gravity drop of the brine through the same 3500 feet."[29]*

For 5000 Barrels Per Day (145 GPM) average disposal, a 5.5" vented gravity flow pipe/casing will suck in lots of air CONTINUOUSLY since the Froude number of ~0.5 is greater than 0.3 to allow for self-venting of air. [30]

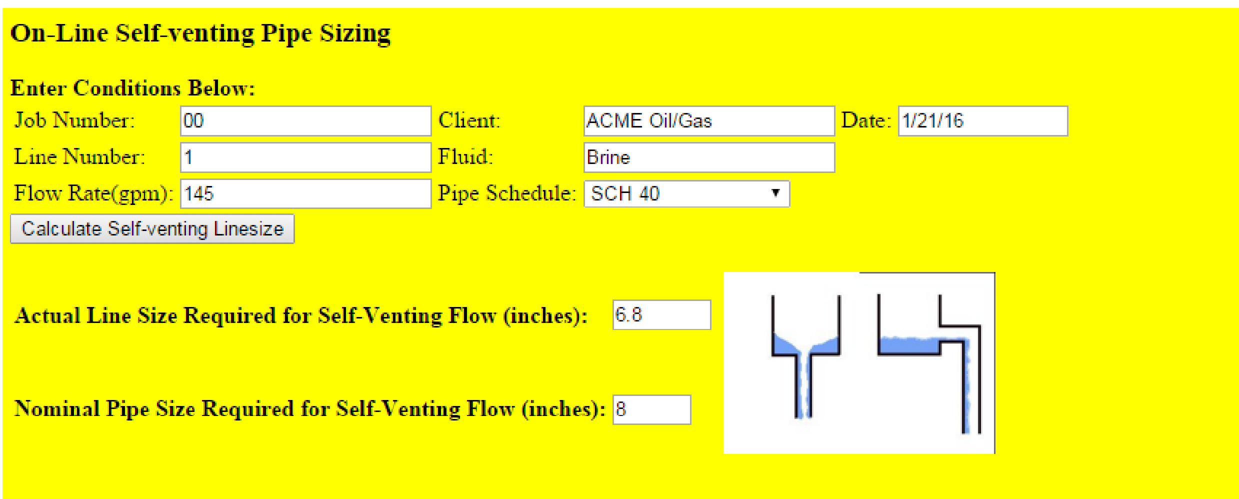

Figure 3: For 145 GPM of gravity flow brine, the casing should be at least 6.8 inches in diameter to allow for the air to vent from the top of the casing, otherwise it will suck lots of air into the earthquake zone. Natural gas + air + spark = Seismic Boom!

2. Well tubing and casings are constructed of carbon steel, a very good conductor of electrical current. This tubing reaches miles into the Earth and can be considered very good grounding rod running deep into the earth [24].
3. Well structures and equipment can be grounded to the tubing and/or casing through the piping. Any electrical charge picked up by the well equipment through conduction or electromagnetic induction from local terrestrial sources of EM radiation can increase voltage

potential and induce electrical current [25]. Well tower structures may receive more local EM radiation through unwanted electromagnetic coupling. Electrical current discharging through the tubing and/casing can increase corrosion rates, which is a common problem in oil/gas wells.

4. The SWD brine has a very high concentration of chlorides in solution and is a very strong electrolytic fluid. This fluid can conduct electrical potential very well and increase oxidation potential and corrosion rates underground and in piping. I have already discussed how chloride ions can start a chain reaction with methane gas.
5. In order to meet increased demand, the SWD wells are pumping the fluids at elevated pressures into the Earth below. Since brine is a non-compressible fluid, the additional pressure on the porous cavities below can compress any existing natural gas pockets and elevate the temperature, which could speed up oxidation rates and chain reactions leading to additional deflagrations and detonations.
6. As shown in figure 2, the location of many of the SWD wells with seismic activity are near many terrestrial sources of EM radiation such as radars, microwave earth stations and microwave relay towers [27], [28]. These are all sources of high gain microwave radiation that refracts and reflects off the overhead atmosphere and is absorbed in the surrounding area. Cell towers now blanket the area also, but are not shown. These antennas can electromagnetically couple with conductive well structures and equipment and increase electrical potential underground.

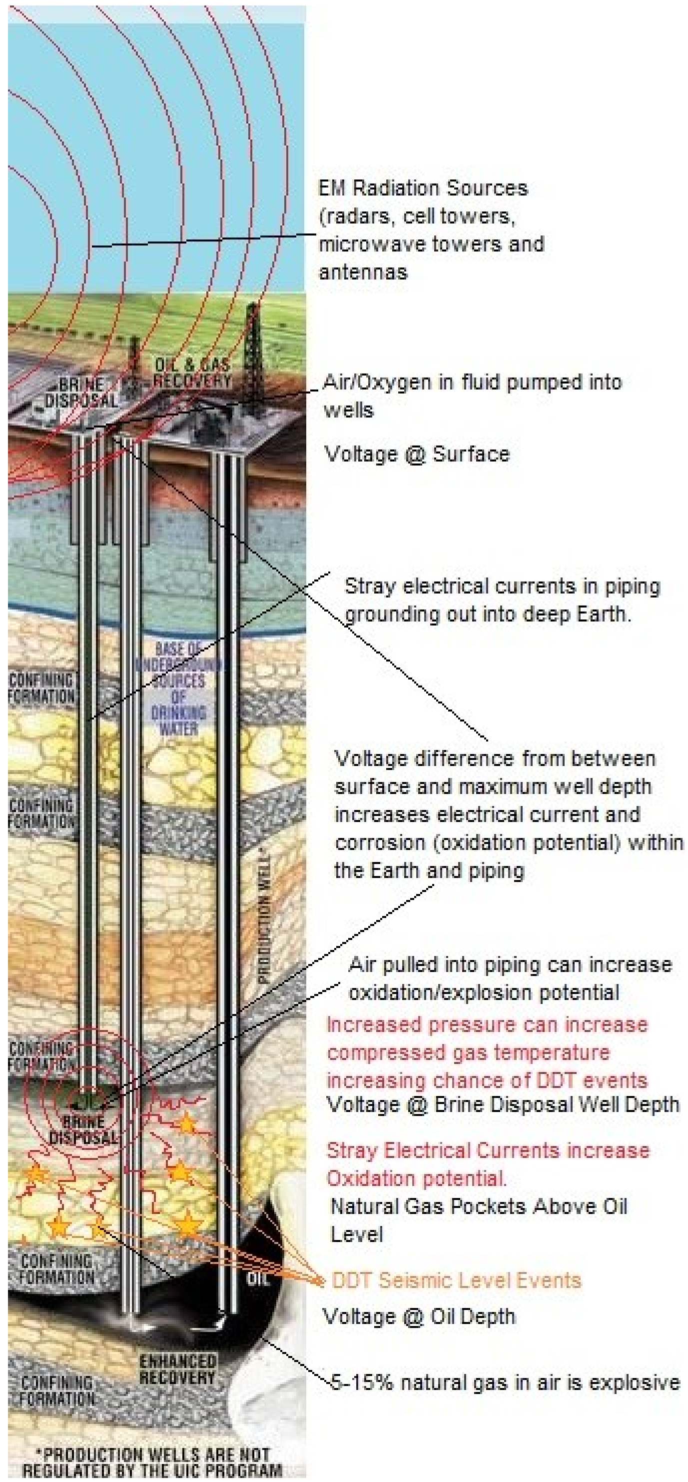

Figure 4 SWD Well design. For gravity flow wells, Froude numbers above 0.3 can operate under vacuum and suck in air along with brine.

Item	Value	Units
brine flowrate	**650**	barrels/day
brine flowrate	18.9	gal/min
brine flowrate	0.042	cu. ft/sec
brine flowrate	0.001	cu. m/sec
tube diameter	**3**	inches
tube diameter	0.076	meters
tube x-section area	0.005	sq. meters
tube x-section area	0.049	sq ft
flow velocity	0.3	meters/sec
flow velocity	0.9	feet/sec
nat gas density	0.05	lb/cu ft
nat gas density	0.80	kg/m3
Froude Number	0.30	
empty pipe depth	5000	ft
water level depth	1524.4	m
air volume in tube	245.4	ft3
air volume in tube	1835.8	gal
air pressure in tube	14.7	lbs/sq in abs
LEL in air	5%	% by vol
UEL in air	15%	% by vol
volume of natural gas (5%)	12.27	ft3 @ STP
lbs of natural gas (5%)	0.61	lbs
HHV methane	51.9	MJ/kg
HHV methane	5.19E+07	Joules/kg
seismic event energy	2.5	Richter scale
seismic event energy	1.41E+08	joules
methane for seismic event	2.7	kg
methane for seismic event	6.0	lbs
# of charges of brine/air req.	9.8	disposal charges
well depth	10000	ft
pressure @ depth	4344	psia
NG gas volume @ depth	0.04	ft3
air volume @ depth	0.83	ft3
mixed NG/air pocket volume	0.87	ft3

Figure 5: Some typical well calculations

Froude Number: Fr = V/SQRT(gu*D)

V = Velocity in tubing/casing (m/s)
gu = g(Sl - Sg)/Sl
Sg = density of gas or vapour (kg/m3)
Sl = density of liquid (kg/m3) - Brine
g = 9.81 m/s2
D = internal pipe diameter (m)

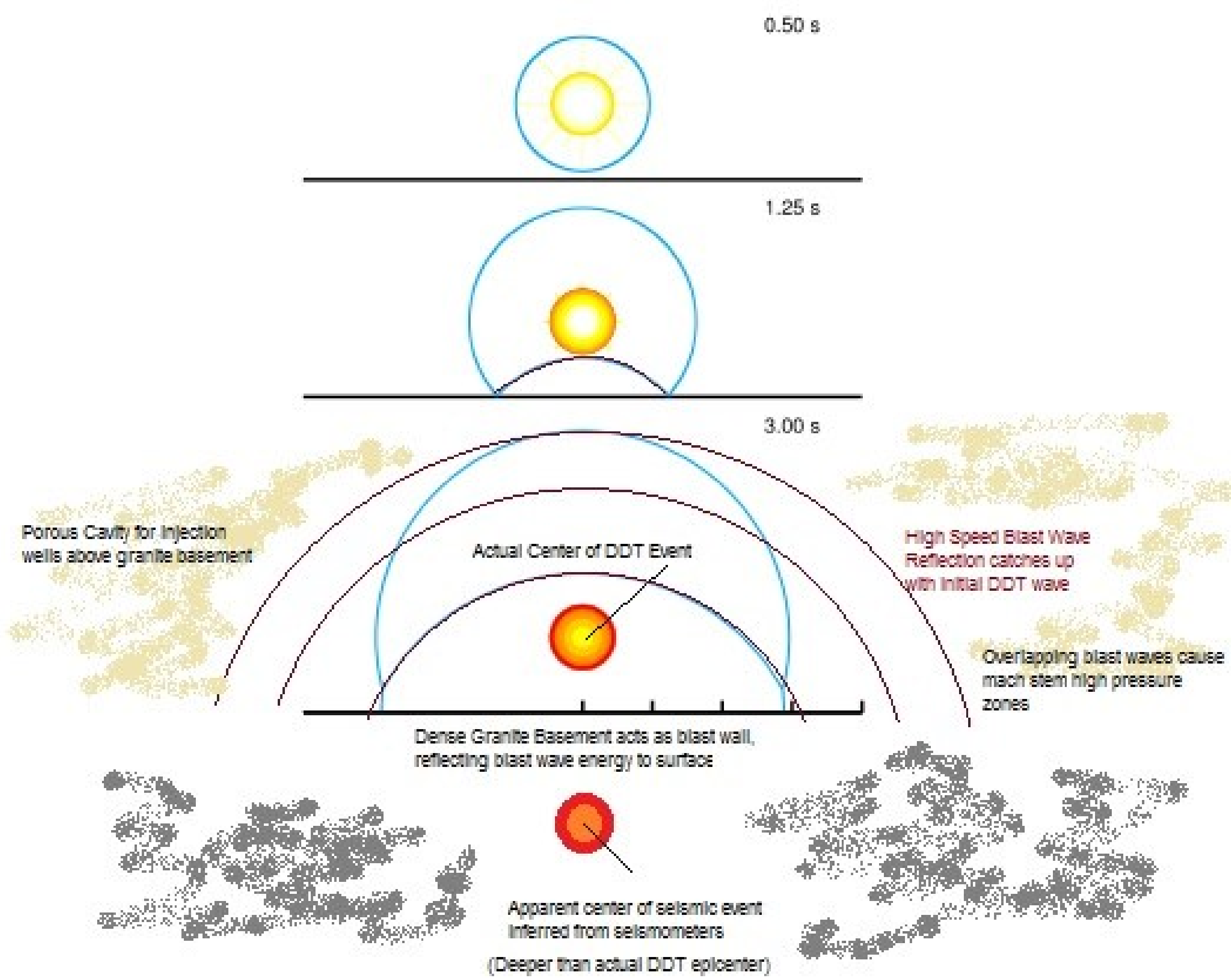

Figure 6: Due to high density granite basement acting like a blast wall [31], the epicenter of seismic events may appear deeper than DDT event and Mach stem events can occur from overlapping blast wave fronts.

Conclusions
Geographic locations and saltwater disposal well design parameters support the hypothesis that the tremendous increase in seismic events associated with brine disposal in some areas of Oklahoma may be associated with deflagration to detonation events of underground hydrocarbons. High pressure, flammable hydrocarbons, oxidizers such as air and electrolytes as well as a local source of ignition support the hypothesis. Gas odors, ultrasonic pressure waves and "booming" sounds as well as Earth electrical currents generated at the time of other seismic events in addition to those in Oklahoma also support the hypothesis. Confirmation of underground DDT events as another source of seismic events in nature in addition to fault rupture/slippage could lead to further Earthquake mitigation and prediction capabilities.

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