REVITALIZING MATURE OIL ASSESTS AN INTRODUCTION TO POWERWAVE^{TM} TECHNOLOGY

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ABSTRACT

In the oil industry, any progress in technologies designed to enhance production is most commonly based on empirical discoveries, and only later followed by attempts to develop a consistent physical theory to explain, analyze and predict field behavior. However, in 1997, a group of scientists and engineers sought to change that mindset. Through a series of laboratory tests utilizing a rigorous theory, this group developed a new fluid flow enhancement technology known as the Powerwave^{TM} Process. Powerwave is an injection technology wherein, with each impulse, a volume of liquid is introduced through a casing or tubing and is forced at high accelerations by downhole devices into the reservoir. The injected fluid then increases the porosity, pressure, permeability, saturation and homogenization of an ever-increasing coherent volume of the porous media through porosity dilation (expansion of the pore throat).

1.0 INTRODUCTION

Powerwave is modeled after the effects of earthquakes on the pores in rocks to stimulate the flow of oil. The technology allows oil producers to tap into mature oil fields in addition to wells that are not producing as well as they should. As early as the 1950s, earthquakes were observed to affect fluid levels in oil wells. Increases leading to enhanced flow were often reported. It was also observed that water/oil ratios changed during an earthquake swarm – sequences of nearby earthquakes striking in a short period of time with no single earthquake serving as the main shock. Wells with initially large water/oil ratios were observed to have lower post-earthquake swarm water/oil ratios and vice versa in wells with initially low water/oil ratios. As a rule, beneficial effects decreased over time following a seismic event.

Earthquakes and explosions are also known to affect underground fluid flow. Large well level fluctuations occurred in the Canadian and American Prairies from 24 to 36 hours after the 1964 Alaska earthquake, long after seismic waves had passed. These effects have been reported for different depths and reservoir conditions and led to the concept of seismic excitation for flow enhancement in the oil industry.

To increase oil recovery, many field attempts in the United States, Russia and China (among others) have been made to induce and couple seismic waves as a method for secondary oil recovery during traditional oilfield waterflooding – a method of secondary recovery in which water is injected into the reservoir formation to displace residual oil. In theory, vibratory forces are thought to promote the movement of oil by diminishing capillary forces – in other words, changes in permeability, viscosity and capillary entry pressure – thereby reducing adhesion between the rock and fluids. This causes trapped oil to be liberated and flow with the waterflood.

2.0 POWERWAVE THEORY

About 20 years ago, Tim Spanos of the University of Alberta completed the initial development of a rigorous theory of porous media mechanics. Previous simplifications and assumptions were examined, found wanting, and corrected, resulting in a theory that is more thermodynamically sound than either Darcy theory for non-dynamic flow, or Biot-Gassmann theory for wave propagation. The new, coupled theory formed the basis of the commercial process, Powerwave. The phenomena of Powerwave and the benefits arising from its applications do not fall within the “conventional” view of porous media mechanics. The mechanics involved in the application of systematic Powerwave are not radical, yet currently accepted porous mechanics models cannot correctly account for the dynamic effects that have been demonstrated (Spanos et al. 1999).

Scientists and engineers working in fluid flow have been taught that the quasi-static Darcy flow paradigm ($q \propto \partial p/\partial \ell$), where gradient is a macroscopically defined quantity ($\partial p/\partial \ell = (p_1-p_2)/\ell$), is a sufficient theory for porous media flow over a wide range of conditions. Perhaps some inability to correctly predict flow rates or dispersion behavior in clays, shales or fractured media is admitted, but otherwise Darcy theory is accepted uncritically.

Similarly, geophysicists working with porous media wave mechanics have been taught that Biot-Gassmann theory is sufficient to describe porous media wave propagation, given a wavelength much greater than the particle size. Neither of these "fundamental" theories is complete, although each may be sufficient for practical purposes under certain restrictive conditions.

2.1 CURRENT FLOW AND WAVE PARADIGMS

Darcy theory is a quasi-static theory, and contains no inertial terms. Thus, when liquid or solid phase accelerations are important with respect to the system flow velocity, one may expect effects that cannot be quantitatively explained. This does not invalidate the Darcy paradigm within the restrictive conditions for which it was stipulated (ie. no inertial effects). However, it does mean that Darcy theory is incapable of predicting or quantifying the effects that we report in this article. This is an important point: because Darcy-based flow theories cannot explain our results, it proves that a more complete theory is required.

The Biot-Gassmann theory of wave propagation in porous media is to wave mechanics what Darcy theory is to flow mechanics, yet Biot-Gassmann theory is based on a set of assumptions that have recently been shown to be inadequate. The two most important flaws are the following:

- Porosity is assumed to be a constant scalar quantity; and,
- The energy in a porous medium can be described by a single-valued function.

Clearly, Darcy theory does not include inertial effects; for example, it is known to be inapplicable to flows involving turbulence (Barenblatt et al., 1992), where internal energy dissipation from inertial effects is important. During the large amplitude excitation applied to the cells in our experiments, inertial effects, sudden acceleration and deceleration of the pore fluid, dominate the flow regime. To overcome this limitation of Darcy flow theory, it is insufficient to introduce empirical factors: a new flow theory including inertial effects must be formulated at the correct scale from fundamental physical principles.

2.2 Development of a New Theory

A new model of wave propagation in porous media was developed to overcome limitations associated with the restrictive assumptions in the Biot-Gassmann theory. The de la Cruz and Spanos model (1989, 1993) utilizes volume averaging in conjunction with physical arguments to construct a set of macroscopic continuum equations that more completely describes wave propagation in a fluid-filled porous medium.

The resulting model consists of coupled, first order macroscopic equations which describe wave propagation in porous media saturated with a single viscous compressible fluid. These equations have been derived and published elsewhere (de la Cruz et al., 1989, 1993), and will not be repeated here. The basic characteristics of the model include inertial mass coupling between the phases, porosity as a variable, energy dissipation because of phase compression, and rigorous incorporation of the dilatational behavior of all phases.

3.0 POWERWAVE FIELD IMPLEMENTATION

The Powerwave theory has been used to develop a simulator which enables reservoirs to be screened for their applicability to Powerwave stimulation and optimization.

To achieve effective Powerwave implementation it is important to deliberately plan Powerwave operations, in light of the specific porous medium properties presented in individual cases. The major operational factors that arise are, Figures 1 and 2:

- *Powerwave amplitude*. This refers to the magnitude of the impact of the impulse of the wave, the part that dictates volumetric inflow of liquids into the porous medium. In almost all cases, it is considered unwise to significantly exceed the local fracture pressure of the porous medium.
- *Powerwave rise time*. This refers to the time to reach the maximum amplitude. The part that triggers dilation. It is imperative to optimize the rise time for a given permeability.

- *Powerwave displacement efficiency*. This refers to the percentage of net fluid volume entering the medium relative to the volume injected during a pulse.
- Fluid injection rate and stroke recurrence rate.

In order to optimize the frequency content of the impulse, calculations using the Powerwave analyzer can be made to approximate the best frequency band. The excitation frequency at which a pore liquid just begins to behave incompressibly is the best to use in practice. This value is affected by:

- *Liquid properties*. Specifically, the water and oil saturations, the viscosity of the major saturant, and the compressibilities of the liquids.
- *Solid properties*. The total porosity, permeability and the shear modulus of the solid skeleton.

However, in any reservoir, there are inherent homogeneities. Variations in all the system parameters listed above, often by significant factors, can exist in a single aquifer. Furthermore, these parameters may be dependent on stress, on temperature, and even on dynamic factors such as shear rate.

Once the proper variables have been determined through use of the analyzer, Powerwave is implemented in an injection well through the use of a downhole device known as the “Dragonfly” tool (Figure 3). The Dragonfly is attached to the bottom of an injection string and creates an impulse with high acceleration of the liquid below a wellbore seal. The sudden acceleration forces the liquid to be expelled through the perforations with a sharp rise time, causing a packet of pressure and dilational waves to propagate from the well. The repetitious impulses create extremely high mixing in the near-wellbore environment (sloshing in and out of the pore space), and the injected fluids will be well dispersed in the porous medium because of the suppression of advective instabilities. As the liquids are injected in this manner the displacement front progresses much more uniformly, reducing viscous fingering and allowing fuller contact of the injected liquid with the reservoir fluids.

4.0 APPLICATIONS OF POWERWAVE IN THE OIL INDUSTRY

Theories, research and hypotheses are one thing, the question is, does it work? In short, yes.

Since 1998 there have been over 175 single well applications and 6 field-scale applications of Powerwave in the oil industry. It has been successfully applied in heavy and light oil, in high and low permeability reservoirs. The method of implementation or system utilized depends upon, among other things, the geology and the fluid viscosity. Powerwave is implemented specific to suit the geological situation. The process can be modified to increase injection and production flow rates, production well efficiency, and oil recovery ratios in a wide variety of configurations.

The fundamental process has also been widely used in the environmental groundwater remediation sector as a means to inject chemical and biological agents into aquifers to gain greater efficiency of injection.

Table 1 outlines the areas where Powerwave has applicability in the oil industry.

Chemicals are added to wells to affect the conditions in the reservoir and achieve better production. In limestones, acidizing is widely used, and acids may also be used to dissolve clay minerals blocking sandstone pores in the near-wellbore region. In many other cases, especially heavy oils, surface-active chemicals (e.g. sulfonates and phosphates with high polarity), diluents (e.g. high API gravity oils or naptha), dissolving agents (e.g. xylene), acids (HCl, HF, formic acids, or mixtures) and other materials are used for a wide variety of reasons to enhance well productivity (Dusseault et al, 2001).

The affects of Powerwave on well stimulation, more specifically, well stimulation with the use of chemicals can be defined by a group of seven heavy wells producing from a single field in the region around Lloydminster, Alberta where production wells were treated with chemicals placed under conditions of aggressive pulsing.

The wells that form the study were concentrated in one field each having at totaled measured depth of about 2000 feet with 16-17°API oil, at the low end of the viscosity range (~1200 cP). The wells are completed in unconsolidated sands of 30-32% porosity; the sands having no tensile resistance, and they produce sand and heavy oil.

Of the seven wells treated, six had several months production history before the Powerwave chemical treatment, therefore average before-and-after data bases could be compared. One well did not have any before treatment data given it had been shut in for many months because it produced 100% water.

Figure 4 provides production details of the seven well program using Powerwave to inject a chemical treatment liquid. Three months pre-stimulation production data for the six producing wells are presented with three months post-stimulation production for the seven wells treated, to give an overall view of the success of the project. The results are summarized as follows (Dusseault et al 2001):

- Before the stimulations, oil rates were approximately stable on a monthly average basis.
- All seven wells experienced considerable increases in liquid production rate; overall, a factor of 2.3 increase was observed.
- The oil production rate increased by a factor of five on the wells.

Perhaps the most significant utility of Powerwave is its impact on liquid injection (water, CO_2, surfactant, etc.) during secondary and tertiary oil recovery.

Let us examine secondary recovery by means of waterflooding. Waterflooding is the most widely used and successful improved oil recovery process. Waterflood oil recovery is dependent on oil saturation at the beginning of the flood, residual oil saturation, connate water saturation, free gas saturation, waterfloodable pore volume, reservoir stratification, waterflood pattern, pressure distribution between injectors and producers, and injection rate. The most common problem observed in waterflooding is injection water seeking zones of highest permeability.

In many oil fields, waterflooding is initiated well before any significant depletion takes place, in order to avoid gas coming out of solution anywhere in the reservoir and to maintain well productivity. However, there are instabilities associated with high rate and high-pressure water injection. These advective instabilities are related to viscosity differences under a driving pressure and include fundamental viscous fingering (mobility ratio controlled), permeable streak enhancement through water flushing by the more mobile phase, coning, and hydraulic fracturing.

The injection of produced fluids in secondary recovery operations may, over time, lead to an impairment of the wellbore regions where injectivity declines and the pressure required to inject increases. At some point, a well stimulation must be performed to re-establish inflow. Though geologic properties such as porosity, permeability, and composition of the disposal horizon has effects on this phenomena the fundamental cause leading to decreases in injectivity is water quality. Water quality can be considered to have physical attributes such as solids, oils, etc., chemical attributes which lead to precipitates being formed in the formation, or both. Either attribute will eventually give rise to pore throat plugging, which in the aggregate, is a leading contributor to injectivity decreases.

For a production company the ability to inject larger volumes of water into a producing formation is an important operational objective as processing rate directly affects production revenue. Volumetrically, where input equals output, increasing input by a factor of two also increases output by a factor of two. If the proportion of water and oil of the output remains constant or tends toward more oil, the production company would recognize greater production revenue. If a formation is not volume balanced with respect to injection/production ratios and the reservoir is in a stage of “filling” the pore space to reestablish pressure drive then the ability to increase injectivity beyond rates typically modeled and measured in the field would also be beneficial as a production company may realize improved production and the revenue associated with it sooner.

Clearly, for any technology to become an industry standard it must outperform established practice. In the case of Powerwave, many of the limitations seen in a conventional flooding approach can be overcome yielding a more efficient flooding program. Table 2 outlines the major differences between Powerwave waterflooding and conventional injection approaches.

Recently, Powerwave has been put to use in a mature oil field lease operated by Wavefront in Rogers County, Oklahoma.

Operations in the Wavefront lease commenced in 1902 and are within 100 miles of Nellie Johnstone No. 1, Oklahoma's first commercial oil well, completed in April 1897. Oil production from the leases is gained from the Bartlesville formation having an average permeability of 19 milidarcies, at a depth of about 500 feet. Production is considered to come from stripper wells where by definition, oil production is less than 10 barrels per day. However, the majority of oil wells are past the “stripper well” definition, falling into the marginal well category where they produce a minimum of 95% water per day as the total percentage of production. Waterflooding has been sporadically applied through the injection of produced water however the low historical injection volumes have not allowed for pore space filling and the reservoir has minimal pressure support as well as minimal reservoir pressure.

The primary focus of Wavefront's Oklahoma operations is to validate the efficacy of the Powerwave Process, more specifically, how Powerwave improves injectivity rates and oil recovery rates for waterfloods in mature assets. In Rogers County five Dragonfly tools are deployed on tubing in water injectors at a depth of approximately 500 feet. Powerwave has provided consistent results with respect to overall improvements in the rate of water injection versus standard injection practices at the same relative supply pressure. As shown in Figure 4 the two to three fold increases in injectivity rate has been independently verified by engineers with a top five global oil producer. The magnitude of the injectivity increase was not unexpected as the process has historically been shown to increase injectivity between 30 to 500 per cent across a range of geological conditions. Production increases using the Wavefront-powered Dragonfly tools have been reported to average 199 per cent over static injection results.

CLOSURE

The Powerwave Process is well understood and is becoming widely known in the oil industry. Numerous field applications since 1998 have shown that it is more effective than traditional waterflooding or conventional well stimulations where liquids are injected. The beneficial effects of Powerwave are chiefly related to the generation of long wavelength displacement waves, which bring dynamic energy to the liquids at the pore scale; this helps them to overcome barriers to flow. Powerwave could potentially change production approaches in heavy and light oil deposits.

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Table 1
Areas of Application in the Oil Sector for the Powerwave Process

Short-term Well Intervention Applications	**Long-term Stimulation Applications**
Matrix Acidization – wellbore cleanup	Permanent add-on to water injectors to improve injectivity rate, sweep efficiency, and reservoir conformance
Remedial sand control	Surfactant and polymer floods
Acid inhibition treatments	CO_2 injection (gas or liquid)
Paraffin removal	Permanent add-on to water disposal wells to reduce the incidence of pore-scale plugging

Table 2 - Comparison of Conventional versus Powerwave Injection

Static Pressure Injection	**Powerwave Injection**
A quasi-static process	A dynamic process
No control over dispersion	Some control over dispersion
Minimal affects on geometrical spreading	Significant affects on geometrical spreading
Dominated by high permeability channels	Not dominated by high permeability channels
For a given reservoir fluid injection rates are governed by the magnitude of injection pressure	For a given reservoir fluid injection rates are governed by injection pressure, rate of change in the amplitude of the pressure pulse, and the dilative capacity of the reservoir rock

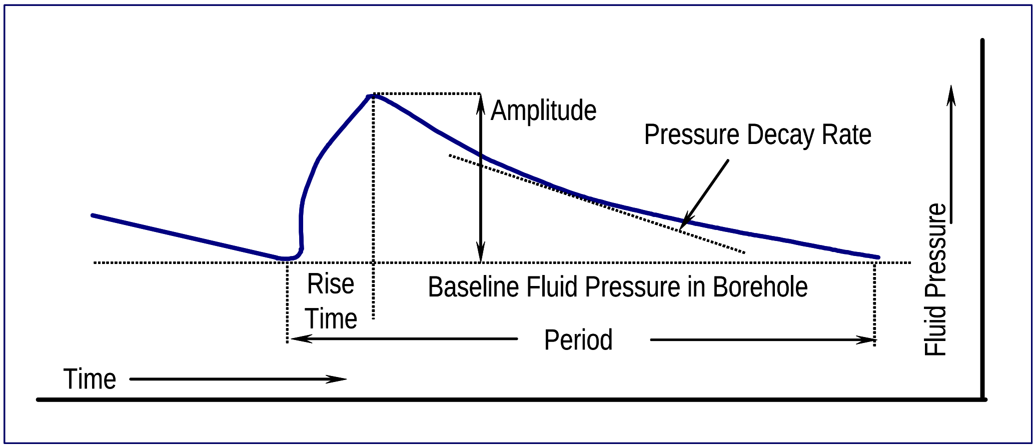

Figure 1 - Idealized Powerwave Waveform

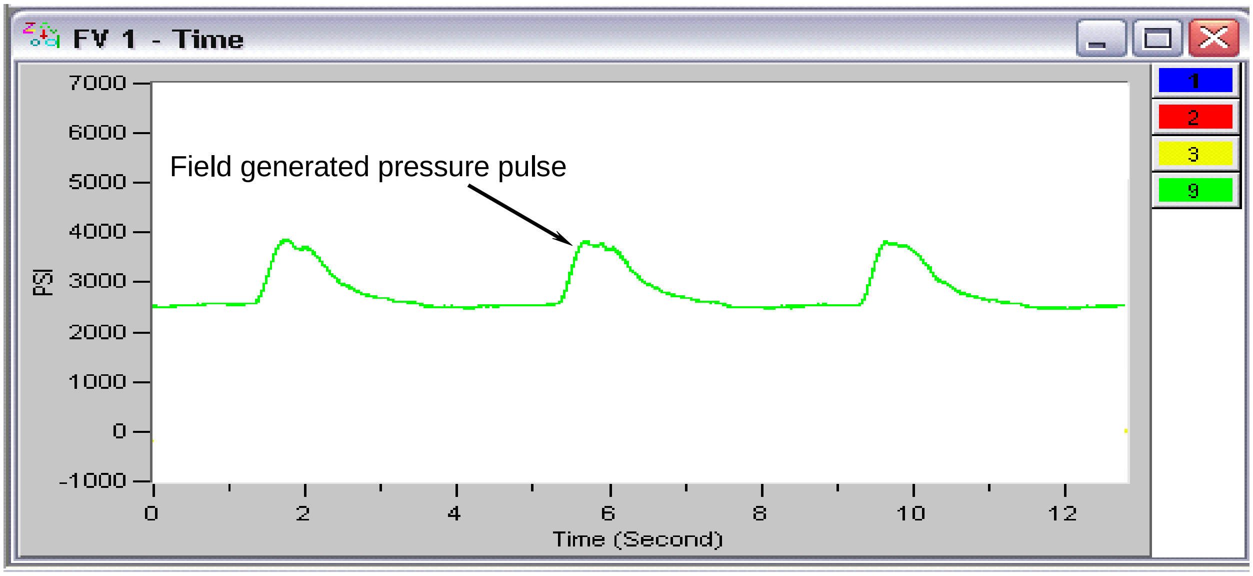

Figure 2 - Pulse Generated by Coil Tubing Deployed Powerwave Tool

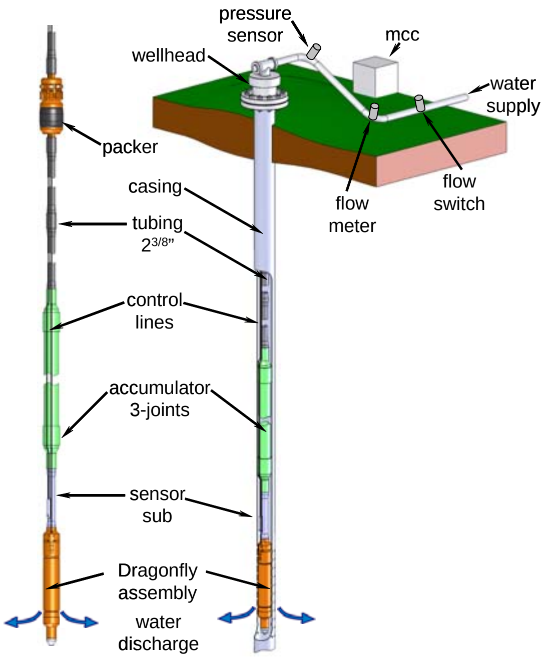

Figure 3 - Injection Well Deployment of a Permanent Dragonfly Waterflood Tool

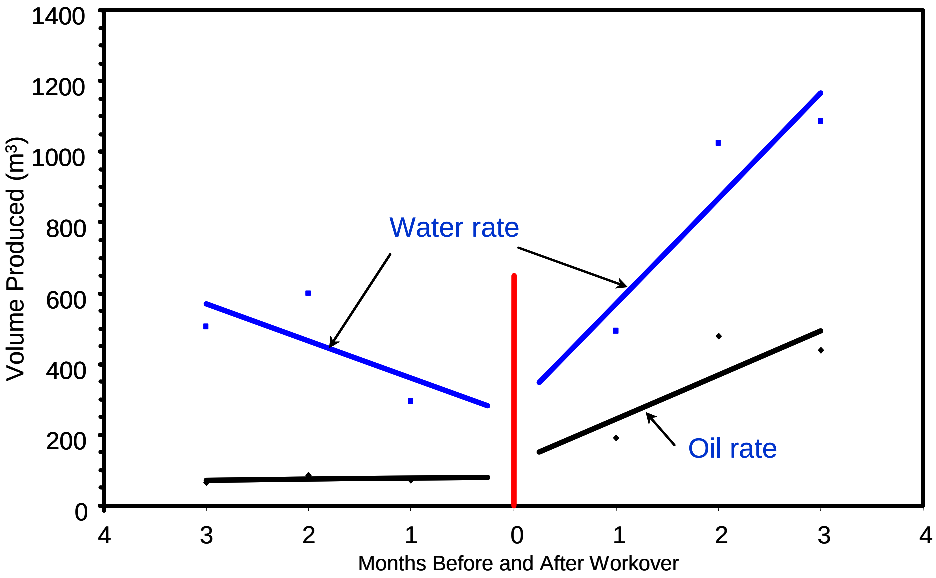

Figure 4 - Comparison of Powerwave versus Static Injection for a Chemical Stimulation

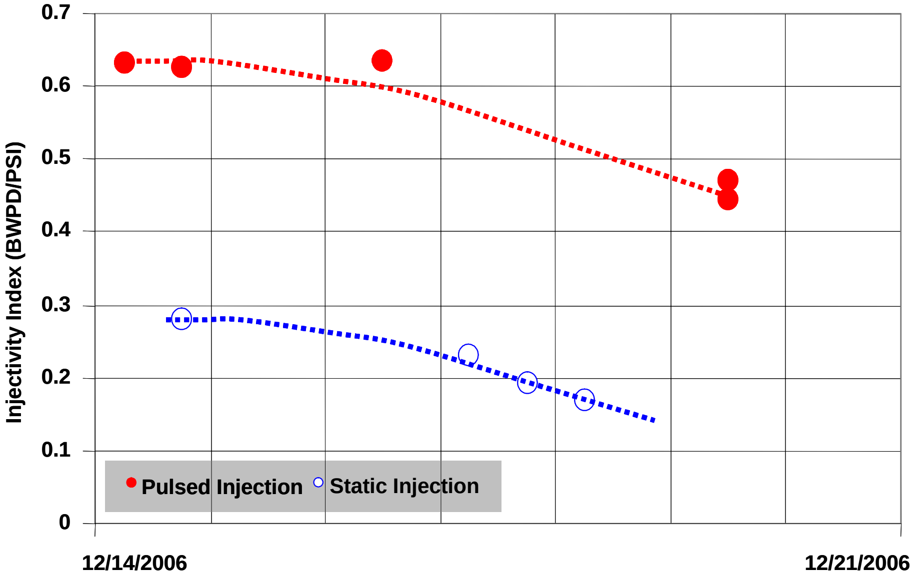

Figure 5 - Powerwave versus Static Injectivity Index for Rogers County, Oklahoma