



**The History and Development of the  
Azimuth Controlled Vertical Hydraulic Fracturing (ACVHF) Technology  
For Installation of Iron PRBs for Remediation of Deep (+40 ft) Groundwater**

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**Overview of the Technology**

The primary objective of this paper is to bring the reader up to date on the advances GeoSierra (formerly Golder Sierra) has made over the past five (5) years developing and perfecting breakthrough technologies for the *in situ* installation of iron permeable reactive barriers (PRBs) at depths that are impossible to reach with conventional methods.

It is well known that zero valent iron PRBs can remediate chlorinated solvent contaminated groundwater by abiotic degradation of the halogenated volatile organic compounds into harmless non-toxic end products. Iron PRBs can also be used to precipitate or immobilize numerous heavy metals in groundwater. The conventional means of installing such vertical iron permeable reactive barriers is by braced excavation, continuous trencher or slurry wall techniques. These conventional installation methods share four major limitations; 1) they are incapable of installing an iron PRB wall at depths greater than 40 ft bgs, 2) they include little if any QA/QC to ensure and validate the PRB is built to specifications, 3) they cause substantial disruption of the surface and subsurface where the iron PRB is to be installed and 4) the excavated soil requires special handling and controlled disposal.

GeoSierra's patented Azimuth Controlled Vertical Hydraulic Fracturing (ACVHF) technology is a breakthrough alternative method of placing iron PRB walls *in situ*, which results in significant cost savings and allows iron PRB walls to be installed at greater depths than conventional technologies. ACVHF technology has been used to install iron PRBs at a number of sites in silts, sands and gravel at both shallow and moderate depths greater than 100 ft. A vertical iron PRB installed by the ACVHF technology can be as thin as 3" or as thick as 9" with a height and length necessary to remediate the entire plume.

The ACVHF technology installs iron PRBs without soil excavation and is thus ideal for sites with surface facilities or underground utilities or sites that are located in urban settings. During installation, the fracture geometry is monitored in real time by GeoSierra's patented active resistivity imaging technology. Before and after the installation of the PRB, hydraulic pulse interference tests are conducted to verify that the PRB has not the conductivity and permeability of the formation. This paper describes briefly the history and evolution of the ACVHF technology and its sibling complementary technologies, which when combined as a unified technology solution, can truly be characterized as breakthrough technology.

**History and Development of ACVHF Technology**

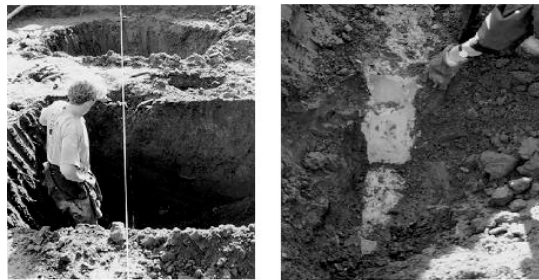
❑ Concept Discovery (1992-1993)

GeoSierra installation technology was conceived from the results of an extensive series of hydraulic fracturing experiments in soils and weakly cemented sediments. Some two-hundred and fifty (250) tests were conducted in a variety of soil conditions and the experiments were excavated to verify the extent, orientation and thickness of the resulting vertical hydraulic fractures. These experiments proved the earlier discovery that a controlled vertical fracture can be created at the required azimuth in the subsurface and what will become an iron PRB wall can then be injected to follow the fracture to a prescribed point. Additionally, it was

proved that a continuous iron PRB wall can be constructed by coalescing the fractures between multiple injection wells. Thus ACVHF and fracture coalescence are the means of building a continuous PRB wall built to specifications in terms of height, depth, length and thickness. It was this sequence of discoveries that ultimately led to the four patents held by GeoSierra associated with its proprietary technologies for trenchless installation of iron PRB walls.

□ Demonstrated Proof of Concept (1994)<sup>1,2</sup>

One of the GeoSierra technology forerunners was field demonstrated as a Proof of Concept under contract to the U.S. Army Corps of Engineers at a site in New Hampshire. These demonstration tests utilized the earliest form of the fracture initiation device consisting of a driven flat-faced probe with an inflatable packer mounted above the probe. The Proof of Concept demonstrated, from the initiation and propagation of twenty-three (23) vertical hydraulic fractures, that fracture azimuth could be controlled and maintained, fracture coalescence of multiple injected fractures could be assured, and fracture thickness of up to 9” could be accomplished.



**Proof of Concept Demonstration of ACVHF Technology**

□ Advances in Fracture Initiation (1995-1997)<sup>3</sup>

The first commercial fracture initiation device developed by GeoSierra was a twelve (12) ft long tool 6” in diameter that was inserted into a 6.25” diameter PVC casing pre-drilled and grouted into the soil to the full depth of the required fracture. The tool was a chain saw cutting device that upon insertion to the required depth cut the PVC casing and grout and could create a five (5) ft long vertical cut in the soil that extended upwards up to twenty (20) ft high. This fracture initiation device was developed for two (2) markets; the shallow environmental application of constructing vertical groundwater permeable treatment walls (iron PRBs) and the much deeper application for petroleum recovery applications in existing hydrocarbon reservoirs.



**First Commercial Frac Initiation Tool**

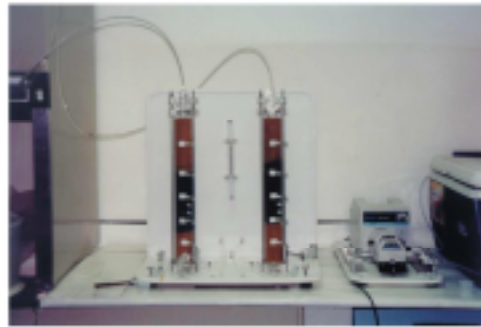
□ Early Permeable Reactive Barrier Installations by GeoSierra (1997-1998)<sup>4,5</sup>

The first two (2) PRB installations used the chain saw frac initiation tool for fracture initiation and the first generation frac iron-gel mix design. These PRB installations were constructed at the Caldwell Superfund Site in Fairfield, NJ and at the Massachusetts Military Reservation (MMR), Cape Cod, MA. Both PRB installations were successful in injecting the iron filings into the subsurface at the required azimuth and to the full height of the vertical treatment wall. However, both installations required additional quantities of enzyme to be injected into the sub-surface to further break down the gel.

❑ GeoSierra breakthroughs in Gel Design and Frac Initiation Technology (1998-1999)

Two major technology advances occurred during 1998 and early 1999; 1) the development of a rapid breaking enzyme capable of breaking even the highest pH iron gel mixtures, and 2) the development of the orientated all metal frac initiation casing system that allows repeated multiple frac injections at various depth (stacked) horizons in order to form a continuous vertical wall. The new enzyme breaker assured the rapid (within hours) clean breakdown of all iron gel mixtures, even those with pH >10. The new casing system had major advantages for the construction of PRBs; namely,

- 1) Repeated frac injections at the same horizon are now possible.
- 2) Fracture coalescence is ensured between frac injection wells, even with slight drilling offsets and/or casing orientation mis-alignment, through the use of casing delimiters and pore pressure relief.
- 3) A stronger and more robust casing system is available for the frac injections.
- 4) Much greater productivity is possible due to the logical sequencing of tasks and simplicity of the system.



Column testing of new rapid high pH enzyme iron-gel breaker.

Installation of new azimuth control frac initiation casing system.

### **New Frac Initiation Casing System and Testing of Rapid High pH Enzyme Breaker**

❑ Commercial Use of New Gel and Casing Technology (1999)<sup>6,7</sup>

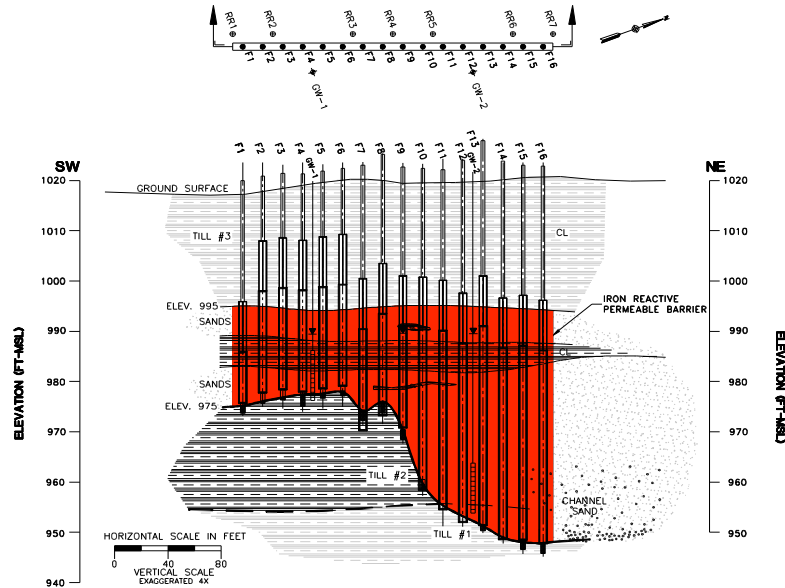
The first applications of the new gel and casing technology as part of GeoSierra's overall ACVHF technology have been successfully utilized at the following sites:

**Caldwell Superfund Site, 1999** - Construction of the PRB extension at the Caldwell Superfund Site in Fairfield, NJ. The installation of the PRB extension was constructed at record productivity rates and achieved clean breakdown of the iron-gel mixtures in 1 to 2 hours.

**Centerville, IA Site, 2000** - Installed a 240 ft long and 75 ft deep iron PRB as the major groundwater remedy at that site. The Centerville PRB was completed in late October 1999 and has delivered excellent performance since then.

**Oakley, CA Site, 2001** – Installation of a pilot PRB, 110 ft in length and moderate depths of 45 ft to 110 ft bgs, was completed in January 2001 and proved to be so successful that three months later the existing Pump & Treat System was shutdown in order to accurately monitor the effectiveness of the PRB. The resulting data was so good that nine months after the installation of the PRB, the Pump & Treat System was dismantled.

**Montross, VA Site, 2002** – Installation of a full-scale PRB, 1,175 ft in length and depths of 5 ft to 44 ft was completed in June 2002.



**Plan and Cross Section of Completed PRB at Centerville, IA**

**Patents issued on the ACVHF Technology:**

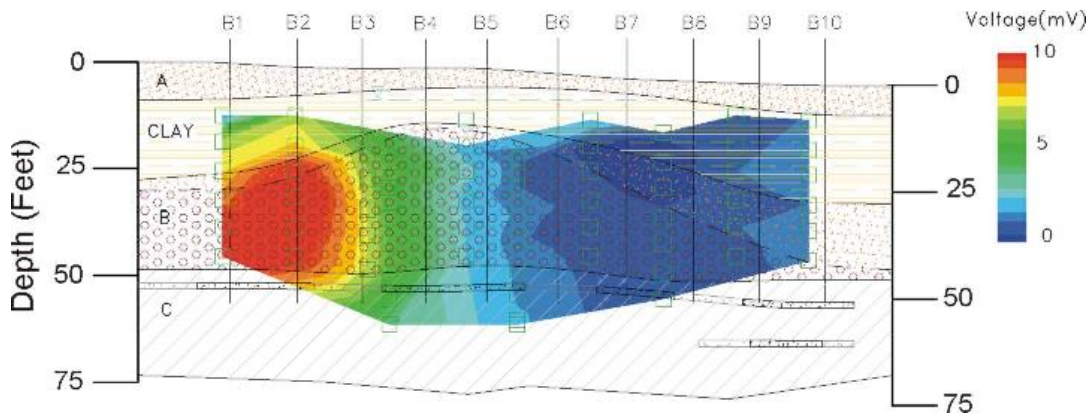
**U.S. Patent No: 5,944,446**      *Injection of mixtures into subterranean formations*  
 Issued August 31, 1999

**U.S. Patent No: 6,216,783**      *Azimuth control of hydraulic vertical fractures in unconsolidated and weakly cemented soils and sediments*  
 Issued April 17, 2001

**U.S. Patent No: 6,443,227**      *Azimuth control of hydraulic vertical fractures in unconsolidated and weakly cemented soils and sediments*  
 Issued September 3, 2002

**Real Time Imagery of Frac Injections<sup>8,9,10</sup>**

The active resistivity method of providing real-time images of injected fracture geometry during construction were conceived and developed over a number of years. The first commercial application of the technology was for the installation of the iron PRB at the Caldwell Superfund Site in Fairfield, NJ in 1997. Since that time the real time imaging technology has been used at all PRB installations by the ACVHF technology to ensure the PRB is constructed as planned according to quality assurance specification requirements.



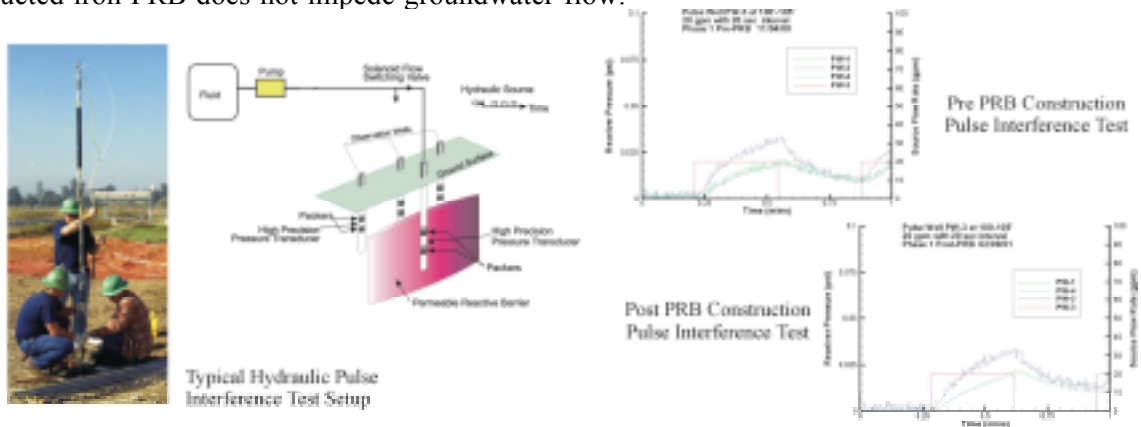
**Real Time Image of Frac Geometry During Injection**

**Patent issued on the Real Time Imaging Technology:**

**U.S. Patent No: 6,330,914** Method and apparatus for tracking hydraulic fractures in unconsolidated and weakly cemented soils and sediments  
 Issued December 18, 2001

**Hydraulic Pulse Interference Test<sup>11,12</sup>**

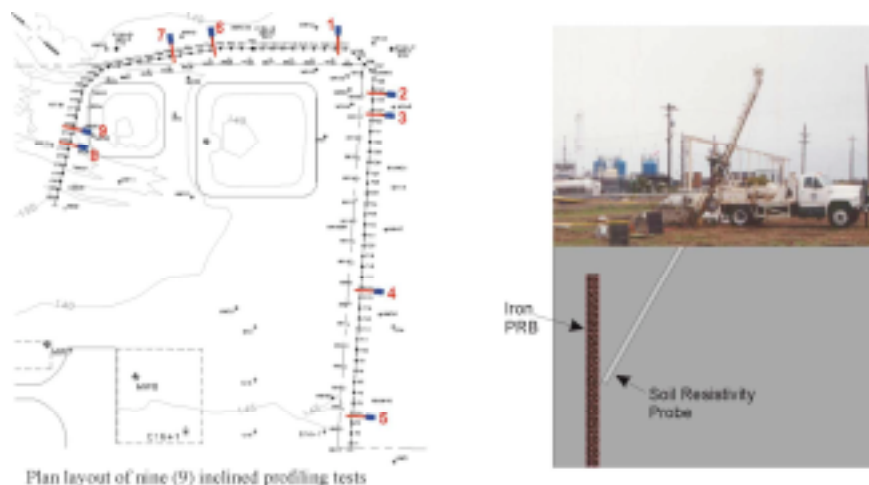
The hydraulic pulse interference test was initially developed for characterizing petroleum reservoir permeability and hydraulic connection between production wells. The method has been enhanced and developments made to the equipment for use in characterizing shallow groundwater sites and to act as a quality assurance technology for both iron PRB and slurry wall constructed systems. The first commercial application of the hydraulic pulse interference test equipment was at the initial iron PRB installation at the Caldwell Superfund site in Fairfield, NJ in 1997. Since that time the hydraulic pulse interference testing equipment, procedures and interpretation software have been utilized at a number of iron PRB installations for both site characterization and quality assurance testing to ensure the constructed iron PRB does not impede groundwater flow.



**Hydraulic Pulse Interference Test for Site Characterization and PRB Quality Assurance**

**Inclined Profiling of PRB Thickness<sup>13</sup>**

The inclined profiling of PRBs for constructed quality assurance has been attempted by drilling and sampling without success. Driven soil resistivity probing technology has been developed to determine the PRB iron thickness by the inclined driving of the resistivity probe through the PRB. The contrast in resistivity of the iron PRB and the native soils enable precise measurement of in placed PRB installed thickness.



Plan layout of nine (9) inclined profiling tests

## **Inclined Thickness Profiling of a Iron PRB utilizing Driven Soil Resistivity Probe**

### **Summation**

GeoSierra ACVHF technology and installation methods have advanced significantly in the past five (5) years. We look forward to applying all that we have learned along with our patented tools and processes to remediate groundwater plumes that in some cases, because of their depth, would otherwise be impossible to reach with an iron PRB wall. In addition to the breakthroughs GeoSierra has achieved for deep iron PRB installations, it is worth noting all of the significant additional benefits to be gained by installing iron PRB walls with GeoSierra's patented ACVHF related technologies:

- With ACVHF, groundwater depths are no longer impenetrable for installation of PRBs – Vertical PRB depths greater than 200' are possible.
- Research indicates iron PRBs to be 1/4<sup>th</sup> of the life-cycle cost of Pump & Treat Systems.
- ACVHF expands the opportunity for significant savings by opening +40 ft depths to PRBs.
- ACVHF technology involves minimal disruption of the surface making it the ideal technology for placement of PRBs in close proximity to building structures, underground utilities and densely populated urban areas.
- ACVHF technology can be employed for both shallow and deep iron PRB applications.

The GeoSierra method of placing iron PRBs in the subsurface is proven. GeoSierra has installed PRB walls at five (5) sites utilizing this technology. The results have been validated, i.e. the walls are in place on the prescribed azimuth and at the top-to-bottom depth, thickness and length as specified by the design. Down-gradient monitoring from each of these walls indicates they are performing as designed.

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