

**Development of a 400 Level 3C Clamped Downhole
Seismic Receiver Array for 3D Borehole Seismic
Imaging of Gas Reservoirs**

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ABSTRACT

Borehole seismology is the highest resolution geophysical imaging technique available today to the oil and gas industry for characterization and monitoring of oil and gas reservoirs. However, the industry's ability to economically do high resolution 3D imaging of deep and complex gas reservoirs using borehole seismology is currently frustrated by the lack of the acquisition technology necessary to record the large volumes of the high frequency, high signal-to-noise-ratio borehole seismic data needed to do 3D imaging. This project takes direct aim at this shortcoming by developing a 400 level 3C clamped downhole seismic receiver array, and accompanying software, for borehole seismic 3D imaging. This large borehole seismic array will remove the technical acquisition barrier for recording the necessary volumes of data to do high resolution 3D VSP or 3D cross well seismic imaging.

3D VSP and long range Cross-Well Seismology (CWS) are two of the borehole seismic techniques that will allow the Gas industry to take the next step in their quest for higher resolution images of the gas reservoirs for the purpose of improving the recovery of the natural gas resources. Today only a fraction of the original Oil or Gas in place is produced when reservoirs are considered depleted. This is primarily due to our lack of understanding of the detailed compartmentalization of the oil and gas reservoirs.

The 400 level 3C borehole seismic receiver array will allow for the economic use of 3D borehole seismic imaging for reservoir characterization and monitoring by allowing the economic recording of the required large data volumes that have a sufficiently dense spatial sampling. By using 3C surface seismic or 3C borehole seismic sources the 400 level receiver array will furthermore allow 3D reservoir imaging using 9C data. The 9C borehole seismic data will provide P, SH and SV information for imaging of the complex deep gas reservoirs and allow quantitative prediction of the rock and the fluid types. The data quality and the data volumes from a 400 level 3C array will allow us to develop the data processing technology necessary for high resolution reservoir imaging.

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INTRODUCTION

This document reports on the development of a long borehole seismic array. A long borehole seismic array is essential to economically record enough data to do 3D VSP imaging or large data volume cross well imaging.

In the past borehole seismic arrays have been deployed using seven conductor wireline technology. The seven conductor wirelines have a limited data band width, limited mechanical strength and are limited to operations in wells which are vertical or with limited deviation. These limitations put severe restrictions on the number of receivers that can be deployed on a wireline based array. Today, the maximum number of receivers that can be deployed on a wireline based array is approximately 20. The tubing deployed downhole array developed by P/GSI and discussed in this report can deploy several thousand receiver levels overcoming the limitations with wireline deployed borehole receiver arrays.

EXECUTIVE SUMMARY

In this report period P/GSI discovered significant manufacturing problems in the seismic cables manufactured by Input/Output for P/GSI on this project. In January through March in three different projects three of the cables failed to perform within the temperature and pressure specifications in P/GSI's purchase orders issued to Input/Output for the five cables. P/GSI started the process of establishing the degree and severity of the manufacturing flaws in the cables. In the previous report periods, for the periods up to December 31, 2002, periods P/GSI successfully finished the assembly and the initial testing of the 400 level borehole seismic array. Initially the data recorded was very good but due to the manufacturing problems with the arrays the quality of the data deteriorated after a couple of surveys. P/GSI concluded the design and the manufacturing of the 400 level borehole seismic receiver array. The design was a refinement and update of P/GSI's first 80 level 3C array.

P/GSI continued to develop the software for processing the borehole seismic data. Much of the work relates to building data management tools for handling the large amounts of data generated by the large borehole seismic arrays. P/GSI was also working on developing velocity model building tools and plotting tools for displaying borehole seismic data together with well logs and surface seismic data. We continued to upgrade the data pipeline tool to manage the input queue of our borehole seismic data into our cluster. In the previous report periods P/GSI worked on developing software for processing 3D borehole seismic data.

The following tasks were concluded in the previous periods:

1.0 Design Receiver array.

- 1.1 Design the array to work with wellhead pressure control equipment.
- 1.2 Design the cables and the geophone pods for the 400 level receiver arrays.
- 1.3 Design the tubing required for deploying the 400 level geophone array.

- 1.4 Design the Geophone pod housings for the receiver array.
- 1.5 Design the miscellaneous deployment equipment for the receiver arrays.
- 1.6 Design the winches for the cables and the geophone pods.
- 1.7 Design the trailers used to transport the 400 level receiver array system to the field.

2.0 Manufacture Receiver array.

- 2.1 Manufacture the five sub arrays for the 400 level analog receiver array. **We have now found that the five sub arrays have manufacturing flaws we are now in the process of establishing the true nature of the flaws has started.**
- 2.2 Manufacture the tubing required for deploying the geophone array.
- 2.3 Manufacture the Geophone pod housings.
- 2.4 Manufacture the miscellaneous deployment equipment for the arrays.
- 2.5 Manufacture the winches for the cables and the geophone pods.
- 2.6 Manufacture the trailer used to transport the 400 level receiver array system to the field.

3.0 Develop Data Processing and Imaging Software

- 3.1 Software Design
- 3.2 Software Framework
- 3.3 Analysis Modules

The tasks during this report period are primarily processing data from tests of the completed system. During an upcoming report periods we will report on the results deploying the full 400 level tubing deployed array and processing of the data using the developed software.

RESULTS AND DISCUSSION

PHASE I - Design and Manufacturing phases for the 400 level, 3C Downhole Seismic Receiver Array.

Task 1.0 Design Receiver Array

Task 1.0 Plan

There are a large number of issues to resolve before the manufacturing of the 400 level array can start. Our current system is operational to 125°C (250°F) to 10,000 ft. High temperature components must be selected that can reliably operate to at least 150°C (300°F) to achieve 25,000 ft. Some of the components are already commercially available and can immediately be incorporated into the high temperature array. High temperature geophones that operate to a temperature of 200°C (400°F) are available from several manufacturers. We anticipate that the design can be achieved in 3 months. It is an

aggressive schedule but achievable because we can draw from the experience building the current 250°F receiver array.

Task 1.0 Accomplishments

P/GSI designed the 400 level borehole seismic array starting using P/GSI's existing borehole seismic array. The cable was updated using a new plastic material and the geophone pods were manufactured in steel rather than polyurethane. We have now however found that the manufacturer Input/Output did not fill the geophone pods with epoxy as specified by their drawings.

Task 1.1 Design the array to work with wellhead pressure control equipment.

Task 1.1 Plan

Interview operators of gas fields to gain a full understanding of the required functions of the array to be acceptable for deployment in a well with high temperatures and pressures. Incorporate design of wellhead pressure control equipment into the design of the 400 level, 3-component clamped receiver array.

Task 1.1 Accomplishments

P/GSI has developed a well head feed through that simultaneously hold the production tubing and the cables. This will allow us to record data in a well that is pressurized.

Task 1.2 Design the cables and the geophone pods for the 400 level receiver arrays.

Task 1.2 Plan

Design the analog cables for the 400 level receiver arrays. We will design the analog cables with a twisted pair for each geophone so the cable design is capable of transmitting data over 25,000 ft long cables. The 25,000 ft of analog data transmission has met with general acceptance among geophysicists that have been consulted on this key issue. In surface seismic surveys analog lines as long as 50,000 ft were and are routinely used. The borehole is furthermore a very quiet environment electrically so very little noise should couple into the arrays. The lead in cable with 126 twisted pairs in our first array is 10,000 ft long with no apparent degradation in data quality.

Task 1.2 Accomplishments

The cable design was modified to accommodate 252 twisted pairs, up from the previous 126 pairs, using magnet wire that connect the geophones in the geophone pods with the digitizing equipment on the surface. This design change was accomplished without changing the outside diameter of the cable. The 252 twisted pair cable allow us to deploy 80 3C levels, 240 channels, on one cable. A new type of polyurethane, Perlthane from Dow Chemical, was chosen as the jacket material of choice. We thought that this new polyurethane would allow us to operate the cables up to an ambient temperature of 300°F. Testing now indicate that the maximum sustained operational temperature for this polyurethane is less than 200°F.

The geophone pod design was changed to include a steel housing and steel end caps. These changes increase significantly the pressure rating of the geophone pods. The estimated pressure rating of the new design if the pod had been manufactured per the manufacturing drawings was 15,000 psi – high enough rating for a receiver array deployment to a depth of 30,000 ft in water. The manufacturer Input/Output tested the new pod design to a pressure of 10,000 psi in a pressure chamber in a 6 hour test. However, we have now determined that all of the geophone pods manufactured by I/O have manufacturing flaws including improperly designed o-rings, voids in the epoxy that was used to fill the geophone pods and improperly mounted 3C geophones.

Task 1.3 Design the tubing required for deploying the 400 level geophone array.

Task 1.3 Plan

Design the tubing required for deploying the 400 level geophone array. In particular we need to review the weight vs tubing strength for the array.

Task 1.3 Accomplishments

After reviewing the different options for tubing a 1.660” tubing was selected as the tubing for the 400 level array. We selected an EUE tubing with 10 Rd threads using an N80 material.

Task 1.4 Design the Geophone pod housings for the receiver array

Task 1.4 Plan

Design the geophone pod housings for the receiver array. The geophone pod housings will protect the geophone pods during the deployment of the array and contain the clamping mechanisms for the geophone pods.

Task 1.4 Accomplishments

The geophone pod housings were redesigned to be able to handle a larger axial load. The estimated strength of the pod housing is now 110,000 – 120,000 lb. In a test the previous design failed at a load of 98,000 lb. We plan to test the new design at a certified testing laboratory later in 2003.

Task 1.5 Design the miscellaneous deployment equipment for the receiver arrays.

Task 1.5 Plan

Design all the deployment equipment to safely deploy the receiver arrays in gas wells.

Task 1.5 Accomplishments

A number of miscellaneous types of equipment has been designed or redesigned as part of this project. The types of equipment include:

1. Sheave wheels designed to guide the cables from the winches to the well.
2. Work plate for safely work over the well
3. Specialized tools for attaching the cables to the geophone pod housings.

4. A new bottom assembly for the array.
5. A new top assembly to control and regulate the clamping of the geophones.
6. A new centralizer to protect cable splices has been designed and built.
7. A new cable protection sub designed to protect the cable through BOP's was designed and built.

Task 1.6 Design the winches for the cables and the geophone pods.

Task 1.6 Plan

Design the winches used to deploy the 20,000 ft cables and the geophone pods.

Task 1.6 Accomplishments

The winches for the geophone pod cables was completely redesigned. The new winch has a sturdy frame which allows lifting and handling the unit without risking damaging the cable. The winch design also incorporated a foot switch which allows one person to both operate the spool and control the cable spooling. The spool can hold up to 20,000 ft of cable.

Task 1.7 Design the trailers used to transport the 400 level receiver array system to the field.

Task 1.7 Plan

To design the field trailers used to store, transport and field the deployment system for the 400 level array.

Task 1.7 Accomplishments

The field unit was completely redesigned, compared with our old unit, allowing secure transport and handling of the equipment to the field sites. The field unit also serves as the operators cab, with power, heating and cooling built in, during the deployment and acquisition of the borehole seismic data.

Task 2.0 Manufacture Receiver Array

Task 2.0 Plan

The overall objective is to manufacture the various components for the 400 level receiver array. The 12 months manufacturing period of this equipment is aggressive but achievable with firm planning and experienced project management.

Task 2.0 Accomplishments

The entire system was initially completed by February 28, 2002. We have now received information that the five 80 level 3C cables must be completely redesigned and rebuilt.

Task 2.1 Manufacture the five sub arrays for the 400 level analog receiver array.

Task 2.1 Plan

The key components of the 400 level receiver array are the five 80 level sub arrays. These five arrays will be manufactured using high temperature standard materials. The arrays are using analog transmission of the data to the surface and the data is recorded on a standard surface seismic 24 bit recording system.

Task 2.1 Accomplishments

Five cables for the 80 level receiver arrays, for a total of 400 levels, were manufactured by Input/Output for P/GSI. P/GSI provided the supplier with the fundamental specifications and the design of the cable and geophone pods but Input/Output guided the detailed manufacturing of the cables. Each cable is 10,000 ft long. The supplier also manufactured an additional 10,000 ft of lead in cable for deeper operations down to 20,000 ft. These cables are now found to be flawed in several way. The flaws include the following: 1. Improper waterblock – the waterblock solidified during the manufacturing of the cable; 2. The o-rings were improperly designed – the o-ring cross section was too small and the space between the two sealing surfaces was too large; 3. The epoxy was not out gassed, which was specified by P/GSI; and 4. The 3C geophones were improperly mounted failing to be mounted in a true orthogonal configuration.

Task 2.2 Manufacture the tubing required for deploying the geophone array.

Task 2.2 Plan

One of the key features with the P/GSI 400 level clamped receiver array is that it is deployed on oil field production tubing or possibly on oil field drill pipe. The tubing used successfully with the current 10,000 ft system is small diameter production tubing. The production tubing is the strength member in the system. It also provides the conduit for the fluid and the pressure used to inflate the packers to clamp the 400 levels of 3C geophones. The current P/GSI 80 level array does not include the feature of allowing tripping in through pressure control equipment. We will incorporate the same equipment in our receiver array deployment system used to trip in Electric Submersible Pump (ESP) systems in live wells.

Task 2.2 Accomplishments

P/GSI had a special run of tubing manufactured to allow deployment in one or several wells. The tubing is manufactured for P/GSI with a certain length specification with a tolerance of $\pm 1/4"$. The tight specification on the length of the tubing provide for a highly accurate positioning of the receivers in the borehole. The tubing otherwise is a standard API tubing so all the handling of the equipment can be performed with standard oil field tools for tubular. We now have enough tubing to deploy our 400 level array in one, two, three, four or five wells simultaneously.

Task 2.3 Manufacture the Geophone pod housings.

Task 2.3 Plan

The geophone pod housings fulfill a dual purpose. The first is to protect the pods during the deployment into the well. The second is to provide the clamping functions for the pod. The clamping function is achieved using a small packer that is inflated through the tubing.

Task 2.3 Accomplishments

330 geophone pod housings were manufactured using an updated design. Together with the existing 88 pod housings, for a total of 418, provide for enough geophone pod housings to deploy a 400 level array distributed in one, two, three, four or five wells.

Task 2.4 Manufacture the miscellaneous deployment equipment for the arrays.

Task 2.4 Plan

A large number of miscellaneous pieces of equipment must be manufactured to support the deployment and operation of the 400 level receiver array. The task here is to make sure all the necessary components are manufactured to make the array fully operational in a safe manner.

Task 2.4 Accomplishments

We manufactured redesigned sheave wheel for the safe deployment of the receiver arrays. Other items manufactured include a bottom assemblies that contain the valves, the top assemblies that are used to pressurize the arrays, work well plates for work over the wells.

Task 2.5 Manufacture the winches for the cables and the geophone pods.

Task 2.5 Plan

To handle the five 25,000 feet of cable with the geophone pods five winches must be manufactured. Each winch will hold the cable for one 80 level sub array.

Task 2.5 Accomplishments

We built five winches each capable of holding up to 20,000 ft of downhole geophone cable. The manufacturer of the spool was working with P/GSI to incorporate P/GSI experience from the field operations into the new design.

Task 2.6 Manufacture the trailer used to transport the 400 level receiver array system to the field.

Plan 2.6 Plan.

Manufacture the field trailers that will be used to transport the 400 level receiver array system to the field.

Plan 2.6 Accomplishments

We decided that we need a separate field unit for each geophone cable spool. A 25 ft field unit was designed and four of these units were built. For the fifth spool we used an existing field unit. The field units are divided into two sections. One section holds the spool with geophone cable and the other section is the spool operators cab. The operators cab is both heated, for cold weather operations and air conditioned for warm weather operation. Each of the five field units have been equipped with a diesel engine powered 13 kW generator so the unit is self contained in terms of power.

Task 3.0 Develop Data Processing and Imaging Software

Task 3.0 Plan

P/GSI will develop advanced data processing and imaging software modules for the 9C borehole seismic data. The processing system shall be closely linked to the acquisition system, and shall be able to handle terabyte 9C prestack seismic data volumes.

Task 3.0 Accomplishments

A number of software modules have been started and is currently being tested on real data recorded in the past. Completed software modules include automated 3C rotation of all the data from deviated wells using selected source points to orient the receivers and automated submission of tasks to a parallel computer. Software modules currently under the development include 3D velocity estimation using a combination of well data, well logs and geologic models.

Task 3.1 -- Software Design

Task 3.1 Plan

P/GSI will design the processing and imaging code for high resolution large data volume 9C borehole seismic data. Initial testing will be performed to aid in design of the object types, their use and communication patterns. Interfaces will be designed to allow for communication with other systems in a secure and speedy manner. The system will be designed to be fast, reliable, fault tolerant, and portable.

Task 3.1 Accomplishments

P/GSI has completed the tasks of identifying the need for developing the 9C software. The software is being tested on real data and the design is judged from the results of the images and the information content of the results.

Task 3.2 -- Software Framework

Task 3.2 Plan

P/GSI shall implement the data flow management and infrastructure for 9C data volumes which will be based on a multi-threaded object flow, which allows for fast parallel as well as pipelined computation on suitable computer hardware. This software infrastructure keeps track of the data types, origin, and destinations.

Task 3.2 Accomplishments

P/GSI has concluded the development of data flow routines to process 3C and 9C data on parallel computer clusters. The design and programming of the data pipe line is a critical part of this process. This pipe line has now being completed. Further refinements in the pipeline have and will be implemented.

Task 3.3 -- Analysis Modules

Task 3.3 Plan

P/GSI will implement the seismic data analysis modules that are essential for high-quality 9C data processing, including but not limited to: modules for 9C wave field separation techniques; modules for 3D velocity model estimation; 3D imaging modules to create 3D images from either the separated data or the pre-stack data objects; and modules for generating 3D fluid flow attributes through the analysis of AVO/AVIS and other advanced analysis on the 3D data volume. The recipient shall ensure the export functionality of partially or entirely processed data, and will implement the linkage and accessibility to external software systems. Data processing modules will be prototyped in the ProMAX data processing system for appraisal of the effectiveness of the module. The above modules will be implemented within the existing P/GSI proprietary borehole seismic processing system.

Task 3.3 Accomplishments

P/GSI has completed the modules to do 3C wave field separation. We are now continuing the development of the 9C wave field separation and 3D velocity model estimation. All the modules are being developed and tested on real borehole seismic 3D and 4D data using 3C and in the future 9C data.

Task 4.0 -- Site Selection

Task 4.0 Plan

P/GSI will work with operators of gas fields to perform at least one but preferably several test and demonstration surveys with the developed hardware to demonstrate how the 3C or 9C 3D borehole seismic data can characterize heterogeneous and fractured reservoirs. We will also demonstrate how the data can be used to characterize the fluid in the gas reservoirs that are imaged. We will deploy a surface 3C vibrator and the 400 level array in several configurations depending on the imaging target of the gas field operator and the wells available for tool deployment. The dataset will be collected in a well in a known fractured reservoir, and the results will be correlated with other measurements and production information.

P/GSI will work with a gas production company to determine the specific objectives for 9C 3D VSP and/or cross well seismic survey(s). P/GSI will work with the gas producer to identify suitable wells, by reviewing geophysical logs, temperature logs, and production information. The site(s) will be chosen to optimize the unique capabilities of the 400 level receiver array and companion software.

Prior to Phase II work, the recipient shall submit to DOE for approval the proposed test sites and site characterization information.

Task 4.0 Accomplishments

A search for a test site is continuing during this period. No site has yet been selected

PHASE II

Task 5.0 -- Field Testing and Data Analysis

Task 5.0 Plan

The recipient shall perform multiple tests of the 400-level receiver array and companion processing and imaging software in selected wells, in a gas-producing field where natural fractures are known to occur. The objective is to generate data and gain experience in the deployment and utility of 3D data sets from the 400 level downhole receiver array.

Task 5.0 Accomplishments

One of the arrays was used for an offshore seismic survey in California. An industry record 7.5 million traces was recorded. Four of the arrays were used for an onshore survey for BP in Alaska. A record breaking 3.0 million traces, for an onshore survey, were recorded in this survey. P/GSI recorded a large single well Massive 3D VSP[®] using a 160 level receiver array for the purpose of imaging a gas reservoir. The results from this survey were published by ChevronTexaco at an industry conference.

Task 5.1 – Deployment of the 400 level receiver array in borehole seismic survey

Task 5.1 Plan

P/GSI shall deploy the 400 level receiver array with either a surface 3C vibrator and/or P/GSI's downhole axial vibrator and an orbital vibrator. The receiver array shall be deployed to record a 9C 3D VSP and/or 9C cross well seismic mode. Data shall be recorded for analysis and interpretation. This data will allow us to map anisotropic properties of the reservoir and further refine the reservoir image.

The purpose is to demonstrate the function and utility of the large 400 level, 3 component, clamped receiver arrays in either 3C or 9C 3D VSP mode.

Task 5.1 Accomplishments

One test surveys was recorded during a previous period. The survey was recorded for Dr. Ernie Majer at LBL recording 9C 3D data to study fractured reservoir imaging using back scattered seismic energy. The system recorded data with outstanding quality. The results from this survey was published at the 2002 SEG meeting in Salt Lake City, Utah.

We recorded a Massive 3D VSP survey using a 160 3C receiver array to a depth of 12,600 ft. Modeling indicates that we should be able to image a gas sand that is less than 10 ft thick at a depth of 14,000 ft. In reality we have detected and mapped a sand that is only 4 ft thick.

Task 5.2 -- Data Analysis and Interpretation

Task 5.2 Plan

P/GSI shall perform data processing, imaging, and interpretation of the 9C 3D data acquired in the field test. The resulting information will be used to evaluate fracture density and fluid content of the reservoir. The ultimate objective is to generate an interpreted data set from a fractured gas reservoirs

Task 5.2 Accomplishments

There was no activity on this task during this report period.