Rapid Acquisition of High Resolution Full Wave-Field Borehole Seismic Data

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SUMMARY

An essential requirement for both Vertical Seismic Profiling (VSP) and Cross-Hole Seismic Profiling (CHSP) is the rapid acquisition of high resolution borehole seismic data. Additionally, full wave-field recording using three-component receivers enables the use of both transmitted and reflected elastic wave events in the resulting seismic images of the subsurface. To this end, an advanced three-component multi-station borehole seismic receiver system has been designed and developed by Sandia National Labs (SNL) and OYO Geospace. The system acquires data from multiple three-component wall-locking accelerometer packages and telemeters digital data to the surface in real-time. Due to the multiplicity of measurement stations and the real-time data link, acquisition time for the borehole seismic survey is significantly reduced. The system was tested at the Chevron La Habra Test Site using Chevron's clamped axial borehole vibrator as the seismic source. Several source and receiver fans were acquired using a four-station version of the advanced receiver system. For comparison purposes, an equivalent data set was acquired using a standard analog wall-locking geophone receiver. The test data indicate several enhancements provided by the multi-station receiver relative to the standard receiver; drastically improved signal-to-noise ratio, increased signal bandwidth, the detection of multiple reflectors, and a true 4:1 reduction in survey time.

INTRODUCTION

The conventional single-receiver approach for acquiring full wave-field borehole seismic data is to deploy a wall-locking three-component geophone instrument in the survey well. The instrument is typically locked at a particular depth to sample the wave-field generated by a seismic source located either at the surface (VSP mode) or in a nearby well (CHSP mode). The receiver instrument must then be moved and locked at other depths in order to sample the full seismic wave-field. Once the full seismic wave-field is sampled, an imaging technique such as tomography or crosswell reflection processing can be applied. The obvious limitation to this approach is the excessive time consumption due to frequent movement of the receiver instrument. When the survey is performed in a production well, the time-consuming nature of the receiver movements results in long shut-in times, and hence delayed production. Therefore, it would be extremely desirable to deploy a multiple-receiver system capable of locking into the borehole at multiple depths and simultaneously sample the seismic wave-field at those depths.

Previous efforts to develop multi-station seismic receivers are summarized in [1]. Prior multi-station receivers can be classified as either fluid-coupled hydrophone receivers [c.f. 2] or wall-locking three-component receivers [c.f. 3]. Although multi-station hydrophone receivers offer the advantages of simple deployment and high frequency response, they lack the vector wave-field measurement capabilities of wall-locked sensors. Additionally, hydrophone receivers are adversely affected by receiver well tube wave phenomena and other fluid-borne noise [4]. In contrast, previous development efforts have resulted in multi-station wall-locked receivers that are limited in their frequency response. Prior wall-locked systems suffer from two significant deficiencies; locking resonances around 200 Hz, and low downhole sample rates. As such, all multi-station wall-locking receivers reported to date are better suited to applications where relatively low frequency seismic energy (< 200 Hz) is propagated from source to receiver.

The objective of this project was to develop and field demonstrate a wall-locking multi-station receiver system suitable for rapid data acquisition of high resolution three-component VSP and CHSP data. In order to provide broadband measurements, wall-locking receivers with a resonant frequency above 1000 Hz were used [5]. Furthermore, in order to use high sample rates, downhole digitizing and a real-time fiber optic link to the surface was implemented. The fiber optic link was crucial to rapid data acquisition since conventional 7-conductor wireline telemetry would require downhole data buffering at the high sample rates.

The resulting system was deployed at the Chevron La Habra, California Test Site to acquire broad-band cross-hole seismic data in a rapid fashion. A common source fan was acquired using the multi-station receiver. For comparison purposes, similar data were acquired using a geophone-based single receiver package.

MULTI-RECEIVER DATA ACQUISITION APPROACH

The multi-station seismic receiver system used in the experiment is depicted in Figure 1. The system consists of multiple wall-locking receivers that are interconnected with standard electrical cables. Each receiver contains three seismic accelerometers whose outputs are digitized by instantaneous floating point (IFP) circuitry. The sample rate of the digitizers is typically 8000 samples per second per channel. Up to 32 receivers (96 accelerometer channels) can be deployed in this fashion.

The digital data which streams out of the receiver packages are Manchester encoded and formatted by the wireline interface unit (WIU) and driven onto Chevron's fiber optic wireline for transmission to the surface. The data streaming to the surface is at a real-time rate of 5 Mbits/sec. The fiber optic wireline also contains electrical conductors which are utilized for power and command signals. The wireline portion of the system is described in [6]. At the surface, the digital optical data stream is converted back to an electrical signal, decoded, and checked for transmission errors. The data are streamed in real-time into a Borehole Data Acquisition System (BHDAS), which is a modified version of the OYO Geospace DFM-480. The acquisition unit performs the functions of both a conventional seismograph and field processing system. The real-time data stream can undergo the following real-time operations within the acquisition system; gain and offset calibrations, stacking, filtering, and storage to mass memory. Once the seismic data is in mass memory, various functions can be performed; wiggle trace display on the CRT and thermal plotter, permanent storage on hard disk or 9-track tape, cross-correlation, and a variety of Q/A routines such as FFT, noise monitors, and AGC. The BHDAS also serves as the control system for the downhole receivers, providing for clamp-motor control, setting of acquisition parameters, and acquiring temperature and diagnostic information from the downhole instruments. The acquisition system is a user-friendly interface for the operator and is fully menu-driven with windowing software.

In the field test described below, four seismic receivers were deployed in a single well using the real-time fiber optic link. Data were acquired four times faster than was possible with a single-level receiver using analog data transmission (also real-time link, but in an analog fashion which is limited to three downhole channels). The acquisition cycle, which includes clamping of receivers, acquisition of 8-second swept data, and unclamping is less than 60 seconds. Each acquisition cycle represents the simultaneous collection of four receiver depths, separated by 10 ft. By moving the multi-level receiver system and the seismic source, data for a tomographic data set can be collected in a very rapid fashion.

CROSSWELL SEISMIC EXPERIMENT

In the Chevron La Habra Test Site field experiment, two separate data sets were acquired from one pair of test holes for the purpose of comparison; one data set was recorded using the multi-station receiver, the other with the Wuenschel single-station three-component geophone receiver described in [8]. The objective of the experiment was to compare the bandwidth, sensitivity, and signal-to-noise characteristics of the two receiver packages, using identical acquisition parameters.

The geology at the Chevron La Habra test site consists of relatively young (Mio-Pliocene) poorly-consolidated clastic rocks, characterized by relatively low seismic velocities (5000-7000 ft/sec for P waves) and low Q values. The apparent dip of beds between the wells is about 17 degrees, with the source well structurally high. The ground surface at the site is flat, with the water table at a depth of about 50 feet. The distance between the source and receiver wells is 400 feet. Both the source and receiver wells are about 2000 feet in depth, and are cased and cemented with 13 3/8" casing to about 80 feet, and 7" casing to total depth. Full waveform sonic, density, gamma ray and caliper logs were run in each well.

Crosswell seismic data were recorded with the receivers located at 10 foot vertical intervals from 100 to 1190 feet. The receiver well was fluid-filled so that the response to receiver-well tube waves could be observed. The seismic source used in the experiment was Chevron's downhole hydraulic axial vibrator [7]. The vibrator was held fixed at a depth of 500 feet, sweeping from 10 to 640 Hz in 7 seconds. No vertical stacking of individual sweep records was employed. The source well was dry during the experiment.

ANALYSIS OF CROSSWELL DATA

The common source gather of vertical component data using the multi-station receiver is shown in Figure 2. The common source gather of vertical component data using the Wuenschel receiver is shown in Figure 3. The raw data for each gather were muted prior to the first breaks, and a 60 millisecond AGC was applied to enhance the visibility of events arriving after the first breaks. Both gathers clearly show P and S wave direct arrivals as well as later-arriving events. Vertical component amplitudes of the P wave direct arrivals on both data sets are diminished when receiver depths are approximately equal to the source depth of 500 feet. This effect is expected due to the vertical polarization, and associated directivity, of the source [c.f. 7].

Of particular interest is the higher signal-to-noise ratio of reflected P wave events on the multi-station receiver. It is expected, given the source directivity, that P wave reflections are more prevalent than S wave reflections in these data. Note, for example, the strong downgoing reflection event which originates from a tight-sand/shale interface at a receiver well depth of 200 feet. On the multi-station receiver this event displays excellent signal-to-noise ratio, with variations in event amplitude and phase easily discernible across the full aperture of receiver stations, while at the deeper Wuenschel receiver stations the event is almost completely lost in the noise. Also note in the multi-station receiver data the upgoing event originating at about 900 feet, which is barely detected by the Wuenschel receiver. Perhaps most noteworthy is the deeper upgoing reflection event on the multi-station receiver gather evident from 250 to 300 milliseconds at receiver levels from 1190 to 800 feet, which is not present at all in the Wuenschel receiver data. Sonic and density log data indicate that this event is probably a reflection from a high impedance highly-cemented sandstone bed at a depth of 1800 feet in the receiver well, which is 610 feet below the deepest receiver level.

Both gathers show S wave direct arrivals whose amplitudes decrease below a receiver depth of about 600 feet. This depth in the receiver well corresponds to the base of a low velocity shale bed which appears to have channeled the direct shear wave energy away from the deeper receiver levels, creating a shadowing effect. Note also the downgoing tube waves in the receiver well, apparently generated by the shear wave energy propagating inside the shale bed waveguide, as well as by incident shear wave arrivals at shallower levels in the well. In general, tube waves are more prominent in the Wuenschel tool data than in the multi-station receiver data.

Spectral amplitude plots for portions of the two gathers are illustrated in Figures 4 and 5. The analyses were performed on traces from 890 to 1030 feet, over a 70 millisecond time window which includes the P wave direct arrivals. In comparing the amplitude spectra it is immediately clear that the multi-station receiver data amplitude spectrum is nearly flat for all frequencies output by the source (up to 640 Hz), while the Wuenschel tool response rolls off markedly beginning around 400 Hz. Given the flat response of the multi-station receiver tool over the entire spectrum of swept frequencies, it seems likely that higher frequencies could have been recorded had they been generated by the source. At 600 Hz the response of the Wuenschel tool is down 30 dB from the response at 400 Hz, while the multi-station receiver is down only 10 dB, a difference of 20 dB.

When comparing the response of the multi-station receiver, which contains accelerometer sensor elements, to geophone-type receivers like the Wuenschel tool, recall that accelerometer measurements include a built-in 6 dB/octave high frequency pre-emphasis relative to geophone (velocity sensor) measurements.

Thus the actual improvement of the multi-station receiver tool's frequency response over the Wuenschel tool is approximately 17 dB for the half-octave from 400 to 600 Hz. In this regard, it is also important to note that accelerometers have an intrinsically lower noise floor at high frequencies than do geophone sensors [5], so that more high-frequency information can be recovered from the accelerometer data. Further, the Wuenschel tool displays mechanical resonances and/or spurious frequency response at 550 and 650 Hz, characteristics which are common in conventional geophone-based receiver systems. As previously noted, the multi-station receiver system is free of resonances to 1000 Hz.

CONCLUSIONS

A crosswell data acquisition experiment conducted at Chevron's La Habra Test Site comparing the multi-station receiver to the Wuenschel single-station receiver showed several significant advantages of the multi-station receiver, both in terms of operational efficiency and improved data quality. A 4:1 reduction in survey time is realized using the multi-station receiver. In a comparison of common source gathers, several significant high signal-to-noise ratio seismic events were identified in the multi-station receiver data which were absent, or only weakly detected, in the Wuenschel receiver data. Also, receiver well tube waves are more prominent in the Wuenschel tool data. Finally, the multi-station receiver tool demonstrated a nearly flat frequency response out to the maximum source frequency of 640 Hz, with a 17 dB improvement at 600 Hz over the Wuenschel tool.

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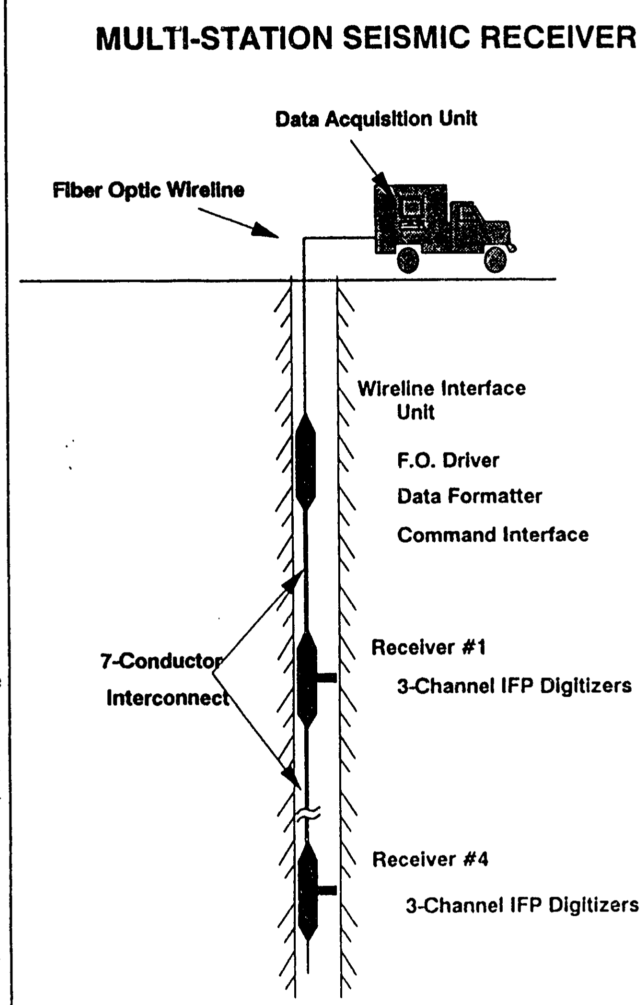

FIGURE 1

SNL/OYO MULTI-RECEIVER COMMON SOURCE GATHER VERTICAL COMPONENT WITH AGC

AXIAL VIBRATOR AT 500'

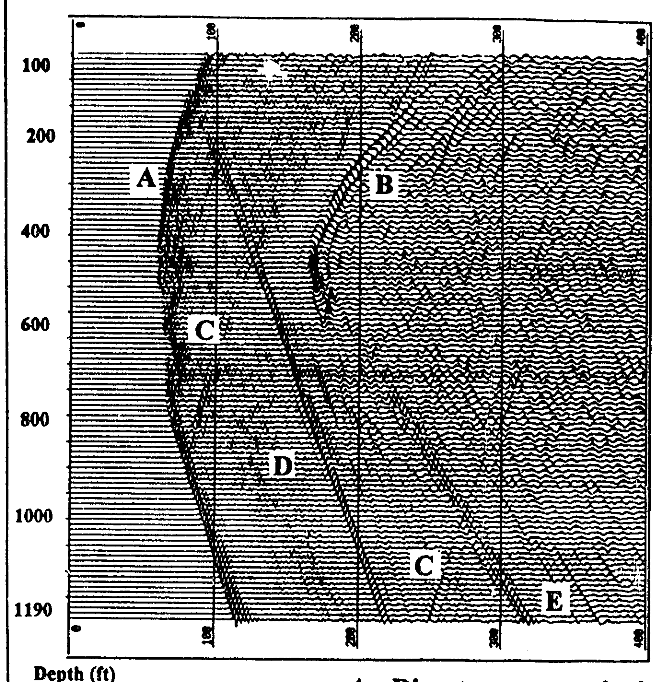

FIGURE 2

A - Direct p-wave arrival
B - Direct s-wave arrival
C - Upgoing refelections
D - Downgoing reflection
E - Tube waves

WUENSCHEL RECEIVER COMMON SOURCE GATHER VERTICAL COMPONENT WITH AGC

AXIAL VIBRATOR AT 500'

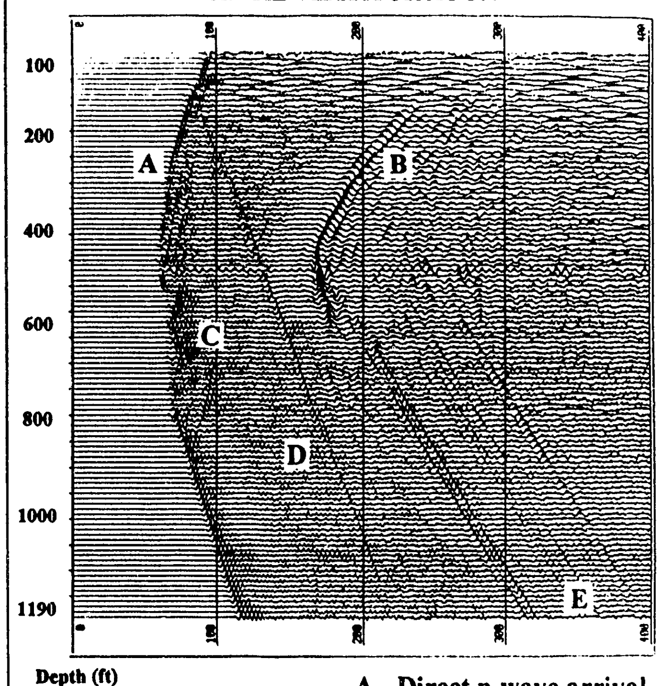

FIGURE 3

A - Direct p-wave arrival
B - Direct s-wave arrival
C - Upgoing refelections
D - Downgoing reflection
E - Tube waves

SNL/OYO RECEIVER

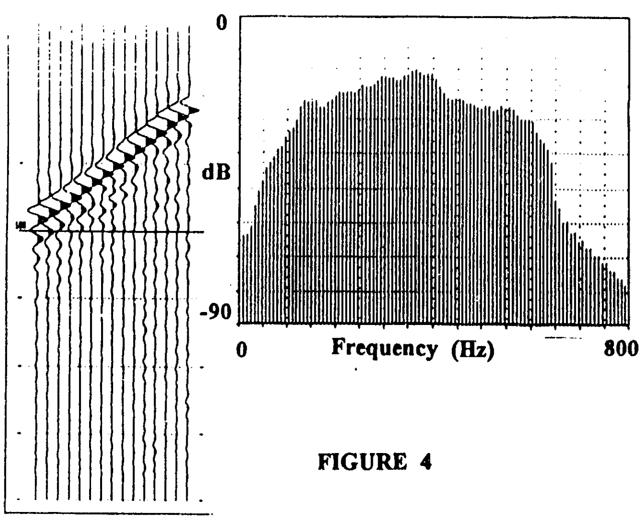

FIGURE 4

WUENSCHEL RECEIVER

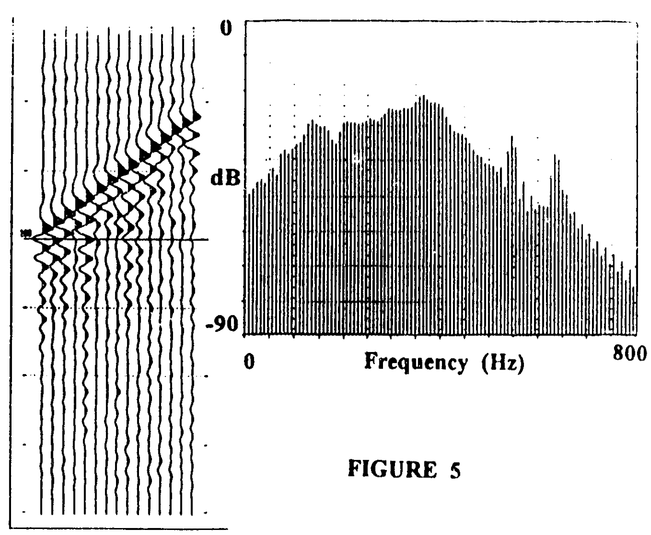

FIGURE 5

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