Reliable and Economical High-Temperature Deep-Borehole Seismic Recording

by Derek V. Manov, Rachel E. Abercrombie,* and Peter C. Leary

Abstract  Recording earthquakes with borehole seismometers has become increasingly popular in recent years as the advantages in noise reduction and also the distorting effects of near-surface rocks, especially sediments, have become well known. Borehole recording can be extremely complex, involving active sensors, special cables, and downhole electronics. Such installations, however, are often not very reliable at the high temperatures reached in active tectonic areas at depths of 1 km and greater. Here we describe a simple and reliable system for 3-component recording of local earthquakes at single and multiple depths greater than 1.5 km and temperatures up to 120°C. Our system was designed and developed for experiments in the Cajon Pass Scientific Drillhole of Southern California. The borehole packages are made of titanium with spring-loaded clamping, allowing easy retrieval. Standard seven-conductor oil-well logging cables are used together with a specially designed cablehead. The data recorded have been used for investigating earthquake source scaling, attenuation in the mid-crust, and also near-surface site effects.

Introduction

One of the fundamental problems facing seismologists is how to distinguish among source, path, and site effects in seismograms. This ambiguity has limited our understanding of such phenomena as earthquake source scaling and amplification of strong ground motion. For example, small earthquakes (<M 3) have been observed to depart from the constant stress drop relationship of larger earthquakes (Aki, 1967). This apparent break in scaling has been interpreted both as a source effect (e.g., Archuleta et al., 1982) and a site effect, with near-surface attenuation limiting the spatial resolution of earthquake sources (e.g., Anderson, 1986).

The most straightforward approach to this problem is to record the earthquakes with sensors nearer the source, beneath any possible near-surface effects. Shallow-borehole installations of a few hundred meters (e.g., Blakeslee and Malin, 1991; Aster and Shearer, 1991) have shown some improvements over surface recordings in lower background noise level and attenuation, but they are not deep enough to be below the whole "site effect." For these reasons, we installed a seismometer in the Cajon Pass Scientific Drillhole, 4 km from the San Andreas fault in southern California, at a depth of 2.5 km (Fig. 1). This instrument recorded local earthquakes, as well as the mainshocks and aftershocks of the 1992 Joshua Tree, Landers, and Big Bear earthquake sequence. After 2 years, it was retrieved and replaced in November 1993 with two instruments at depths of 1.5 and 3 km, which are still in place. These deep recordings have provided us with a wealth of information concerning earthquake sources, path, and site effects.

The downhole sites are extremely quiet, well away from any surface noise, and many earthquakes too small to trigger the local network have been recorded. Abercrombie and Leary (1993) use these recordings of small earthquakes to show that constant stress drop scaling holds from about M 0 to M 7, and this is confirmed in a more detailed study by Abercrombie (1995). Abercrombie (1996a) also finds that the b value is constant (approximately 1) above M 0.5 in this area, and this is in good agreement with the self-similarity of the earthquake source process. Leary and Abercrombie (1994a, 1994b) use the downhole recordings to calculate intrinsic and scattering attenuation in the upper crust. Abercrombie (1996b) compares recordings made at different depths with those at the wellhead and a nearby granite site to calculate directly the site effects at this location.

Although seismograms recorded at depth are simpler and clearer than those recorded at the surface, the actual recording of them is more difficult. The principal problems are the high operating temperatures and pressures. These difficulties have been overcome in previous studies of hydraulic fracturing (e.g., Fenton Hill; Fehler and Phillips, 1991). In such studies, however, the timing of the seismic activity is known, and the seismometers only have to be in place for a

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few days or weeks. Short-term, high-temperature installations of a few hours to days are also all that is required for VSP studies of petroleum and geothermal reservoirs. Tectonic seismicity, on the other hand, cannot be easily predicted, and as the area around Cajon Pass is not particularly active, it was necessary for the instruments to work for months to years to obtain useful volume of data. Below we describe the method used to instrument the Cajon Pass Drillhole. The principal requirements are long-term reliability, relatively low cost, and high-sensitivity recording.

Instrumentation Overview

A borehole seismic installation usually includes the following principal parts: (1) sensor; (2) pressure housing; (3) clamping and coupling mechanism; (4) cablehead; (5) cable; and (6) data amplification, digitization, and recording system. The aim of a successful experiment is to choose each constituent part to maximize the quality of the data recorded. These choices are governed by the type of data required, the available technology, and the budget. Our selections were principally governed by our decision not to send power downhole. We use a completely passive system. This decision was made chiefly in the interests of long-term reliability. In borehole installations, high-pressure fluid attempts to leak into the instrument package and cablehead. It can bypass seals and invade epoxy resins causing 60-Hz noise and deterioration of the leakage resistance. In a passive installation, as long as there remains a channel with a signal-to-noise ratio high enough for triggering a recording system, 60-Hz noise can be filtered out. If power is sent downhole, however, any leakage rapidly leads to electrolysis and loss of the experiment. For example, one month is the longest period of deep seismic recording with an active sensor known to the authors at temperatures and pressures similar to those in the Cajon Pass Scientific Drillhole (P. W. Kasameyer and P. Harben, personal comm., 1995). Also, active sensors and other downhole electronics would have increased the cost of our installation significantly. The chief advantage of an active accelerometer would have been to record lower-frequency (<1 Hz) signals. We were chiefly interested in high frequencies (up to a few hundred Hertz), as these are most affected by site effects. Since passive sensors are available that record these frequencies, the decision not to use power downhole is not one we regret.

Our deep seismic recording at Cajon Pass occurred in two phases. We describe the installations in chronological order, noting what changes and improvements we made to our design in phase II as a result of what we learned in phase I.

Phase I Deployment

In our phase I deployment of August 1991 to August 1993, we deployed a single sonde at a depth of 2.5 km (temperature 105°C, pressure 26 MPa). At this depth, the package was 2 km into the granitic bedrock.

Sensors

We selected 10-Hz geophones as sensors (Table 1), as they are the lowest-frequency geophones with good output characteristics readily available that work reliably at high temperatures. Lower-frequency geophones have larger masses, which cause creep in the springs at high temperatures. Also, they have very limited tilt tolerance on the horizontal components (<2° at 4.5 Hz) and leveling the downhole package was not attempted. The 10-Hz geophones have a tilt range of 56° for vertical and 26° for horizontal. This is larger than that likely to be encountered in the Cajon Pass Drillhole, which is relatively straight (maximum inclination 5°; Wicklund et al., 1988). Finally, a 1- to 4-Hz P wave

Figure 1. The location of the Cajon Pass Scientific Drillhole. (a) Map showing local faults and earthquakes recorded by the network during 1989–1994. (b) Cross section showing the location of the instruments in the borehole (after Silver and James, 1988).
typically has a 1- to 5-km wavelength that is minimally affected by the uppermost crustal site effects. The low noise levels enabled signal frequencies as low as 2 Hz to be recorded for small local earthquakes (Abercrombie and Leafy, 1993) and even lower for larger more distant events (Abercrombie and Mori, 1994).

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Seismometer Package and Clamping Mechanism

The mechanical and functional parts of the deep-hole sonde are shown in Figure 2. The two basic elements are the sensor housing and the clamping mechanism. Locking the sonde into place in the borehole was accomplished by a motor-driven release mechanism with a spring-loaded clamping arm pinning the sonde against the borehole casing with a three-point system. The three-contact-point configuration minimizes ringing and vibration while maximizing sonde coupling to the casing (Leary et al., 1990). The three-point system is also important in keeping the sonde vertical in the borehole, which is required for the horizontal geophones to remain within tilt specifications. The package was not cemented in place (providing the best coupling) because we wished to be able to retrieve and redeploy the sonde, and also we were required to leave the borehole accessible for future scientific use.

Vertical and horizontal positioning is achieved by symmetric triangulation using a single clamping arm for stability against the sidewall (Leary et al., 1990). The spring-loaded pinning arm has greatest stabilizing action if it is positioned near the middle of the sonde with two diametrically opposed carbide gripping pins at either end of the sonde package oriented to position the sonde centrally in the borehole (Fig. 2). A high-temperature reduction gear motor is used to release the sonde's pinning arm at the selected depth in the borehole. The motor rotates a threaded rod that in turn trips a release pin, allowing a series of preloaded stainless steel
coil springs to expand, bringing the clamping arm to its fully extended position. The force of the springs and geometry of the clamping arm is calculated to provide maximum tension near full arm extension. During release of the clamping arm, no moving parts expand against the ambient borehole pressure. Only rotational forces are used in this design to minimize the forces required to release the clamping arm.

The high temperatures at depth, extended deployment time, and potential for electrolysis limit options for recovery. Mechanical or motor-driven release mechanisms are not used in our present design to disengage the arm from the borehole wall as they are unlikely to function after 2 to 5 years in the borehole. The sonde is designed to be capable of being pulled up the borehole against the friction created by the spring tension on the clamping arm on the borehole wall. The increased force from the spring tension and friction amounts to about 3200 N (8200 N total at full depth) when sliding against the wall. This method works very well in a cased hole, such as the Cajon Pass Drilling, but could be more difficult if attempted in uncased holes.

There is sufficient movement of the arm to allow for locking in a 7½-inch cased hole. By utilizing longer or shorter clamping arms, the sonde may be pinned in a wide range of hole sizes (the Cajon hole is 6.5 inch I.D. at 2.5 km) down to the minimum diameter of the sonde (100 mm). The optimum clamping arm angle is 45°. Maximum clamping arm tension to hold the sonde securely against the borehole wall is maintained by using the appropriate number of stainless steel springs in the lower bay.

The sonde and locking mechanism are constructed primarily of titanium with some minor parts of stainless steel. Titanium was chosen because of its excellent strength-to-weight ratio and its corrosion resistance. A light-weight sonde is easier to secure in the borehole; less weight requires less spring tension to clamp the package to the borehole wall. To limit the occurrence of electrolysis, the use of dissimilar metals was avoided where possible in the fabrication of the sonde, cablehead, and locking mechanism. In the elevated temperature, but anoxic, conditions of the Cajon Pass Drilling, the combination of titanium and stainless steel does not appear to have caused problems. Hydrostatic pressure on the sonde in the borehole at a depth of 2.5 km is about 26 MPa with a corresponding temperature of 105°C. Table 1 contains the basic mechanical and electrical specifications of the sonde and the wirelines.

During installation, the sonde first must be clamped to the sidewall of the borehole, and then the weight of the cable is released by lowering an additional length into the hole. Depending upon the size of the hole and type of cable, 5% of the total cable length is usually adequate to release the tension on the cable and to isolate the sonde from mechanical noise injected at the surface. Decoupling the energy transmitted to the sonde from the surface along the electromechanical cable is necessary to achieve the minimum noise environment of the borehole.

Cablehead

A standard Gearhart-Owen seven-conductor 1½-inch quick change cablehead was used during the phase I deployment. The quick-change cablehead is designed for well logging tools and is generally not intended for extended deployments. A single Viton boot assembly is used in the termination of the seven cable conductors. A Dow Corning silicone compound (DC111) is used to fill the chamber of the cablehead around the boot and helps prevent leakage by limiting access of the corrosive materials to the conductors.

Cable

A standard 7/16-inch seven-conductor electromechanical oil-well logging cable (Rochester Dataline) was chosen for best all-round characteristics. We were able to purchase this used cable, but in excellent condition, for less than half the price of new cable. The cable is rated to 149°C (Teflon conductor wireline is rated to 232°C). Six conductors are dedicated to the three geophones, and the central conductor plus the outside armor are used to drive the motor release mechanism. Cross talk occurs from both capacitive and inductive coupling between the wires of the cable. The larger the diameter cable, the less the capacitive coupling and the lower the impedance, but the weight factor increases significantly for longer cables. Most cables must be self-supporting through internal or external armor, and the best designs are nonspiraling so that twisting is minimized as the weight is increased during deployment.

Recording

The unamplified analog output from the cable was fed directly into a 16-bit RefTek data recorder. These units can support a throughput of about 3000 samples/sec with simple triggering parameters. We used 500 samples/sec on the three downhole components and 250 samples/sec for the 3-component surface instrument.

Discussion

Seismograms and spectra recorded on the vertical component at a depth of 2.5 km and at the wellhead (Fig. 3) show the advantages of recording small earthquakes downhole. Sonde resonance (~55 Hz) was a problem only on the horizontal component perpendicular to the clamp arm. In many recordings, a 155-Hz resonance is also seen that probably originates in the borehole casing.

After about 7 months, gradual leakage in the cablehead began reducing the cable pair resistances to less than 50 kΩ (from over 200 MΩ), admitting 60-Hz noise, 50 times the background noise level on the vertical component. This was easily filtered in postprocessing but would probably have terminated the experiment due to conductor electrolysis if we had been sending power downhole. After about 6 months, the coil windings of one horizontal geophone began to deteriorate as a result of the elevated temperature. This led to an 80% decrease in output amplitude over the next 15
months. As there was no detectable change in the frequency response, and the amplitude degradation could be determined from the resistance measured across the geophone at the surface, this deterioration could be corrected for and the output reliably used. This unintentionally “low-gain” geophone was the only one to record the Landers earthquake (M 7.3, 100-km distance) on scale (Abercrombie and Mori, 1994). The geophones used in the phase II deployment performed better (see below). Upon recovery, it was determined that a design change was needed in the cablehead to minimize leakage in the next installation.

Phase II Deployment

In November 1993, we installed two deep seismometers at depths of 1.5 and 3 km in the Cajon Pass borehole to investigate in more detail the near-surface effects on earthquake seismograms. We accomplished this with two packages on separate cables, as described below. These sondes were nearly identical to that used in phase I. The same type of sensors and clamping mechanisms were used in both packages, although the 1.5-km package was slightly longer with a longer clamping arm since the casing diameter is larger (8.5 inch I.D.) at that depth. At 1.5 km, the temperature is only 65°C, and the pressure is 15 MPa. A standard Gearhart-Owen-type cablehead was considered adequate. The primary cause of leakage in the phase I (2.5 km) package was through the cablehead; therefore, a new cablehead was designed for the deeper instrument (120°C, pressure 29 MPa), as described below.

Cablehead

For the 3-km sonde, we designed a new cablehead based on one developed by the Los Alamos National Laboratory (Dennis et al., 1985). The important elements are shown in Figure 4. Kemlon high-temperature feed throughs are used for each termination on the seven-conductor wireline to separate and insulate the individual conductors with silicone rubber boots. To keep water and other corrosive liquids from contact with the rubber boots and feed throughs, Krytox, a "heavier than water" silicone fluid, is used to fill the upper chamber of the cablehead. The lower section includes a standard female seven-pin Gearhart-Owen-type connector isolated from the water and pressure. This standard cablehead
has only one boot assembly for the seven conductors and is therefore more prone to leakage. Our hybrid cablehead provides enhanced temperature and pressure performance but still allows mating with existing Gearhart-Owen-type seven-conductor borehole tools. For our installation, it was important to be able to disconnect the sonde from the wireline and feed the cable through the wellhead and, subsequently, reattach the sonde underneath since it was too large to pass through the main valve fitting. For other design configurations, the Kemlon-type connector cablehead may be made integral with the sonde package.

Cable

Standard, relatively inexpensive logging cable comes only with a maximum of seven conductors. Although two packages could be attached to one cable, the cable above the shallow package would be carrying the output of six geophones. This could be accomplished using one conductor per geophone and a common ground. However, such a configuration leads to considerably higher cross talk, especially at the higher seismic frequencies, due to the relatively high output impedance of the geophones. Common mode rejection is increased significantly with two conductors per geophone. A specially made cable with 13 or more conductors costs approximately four times as much as a new seven-conductor cable (eight times as much as a used one), and this option was beyond our budget. We therefore used a separate seven-conductor cable for each package. We reused our 7/16-inch cable at 1.5 km and purchased a used 5/16-inch cable for 3 km. Keeping the packages completely separate also meant that if one unit experienced problems, the other would be unaffected. Also, since cableheads appear to be the weakest point in the installation, separate cables meant only one cablehead per package. If the packages were in series, then a cablehead would have been required both above and below the upper package, increasing the number of weak links.

Installation

Our phase II installation was completed in November 1993 using two oil-well logging trucks and two sheave setups on a stinger truck. The 3-km sonde was lowered in first and clamped. While keeping cable tension on the first, the second sonde was lowered and clamped into place. If the second sonde should happen to constrict upon the first sonde’s cable, the clamping force is not sufficient to damage the double-armored cable. The deep (3 km) sonde was then slackened 132 m, and the cable was clamped at the surface with a specially designed dual-head cable-clamp system. The 1.5-km sonde cable was then slackened with 83 m of extra downhole and then clamped at the surface. No problems were encountered with lowering the two cables into the well. Retrieval has not been attempted, but we will reverse the deployment sequence and do not expect complications.

Recording

Short-term recording of the 2.5-km sonde at 1000 samples/sec showed useful signal to at least 300 Hz so that in phase II, we recorded both deep instruments at 1000 samples/sec using a separate RefTek for each level. We also used a third RefTek to record a nearby 300-m deep package and a surface seismometer at lower sampling rates. In order to ensure correct timing on all three RefTeks and to trigger all levels from the 3-km instrument, we used a small triggering box to pass the signal from one GPS clock into all three RefTeks and to pass event trigger information from the deepest instrument to the other two. On account of the RefTeks having a floating ground reference, this triggering box had to use optically isolated trigger signals to prevent high levels of 60-Hz noise from being induced upon the signal inputs of the combined system.

Discussion

The two deep seismometers have been working well for over a year at the time of writing. Some leakage has occurred, and the resistances are down to 100 kΩ, but no serious 60-Hz noise has been encountered. The noise level in the second experiment is about five times higher than in the
Concluding Remarks

Our simple and relatively inexpensive system for recording local seismicity at depths of over 1.5 km has proven very reliable and successful. The limitations on the system appear to be the cablehead, which has been the primary source of leakage. The maximum deployment time is a function of both borehole temperature and depth of the sonde with increasing temperatures and pressure decreasing markedly the effective operational time. Teflon wireline and a further refined cablehead could possibly extend the lifetime, but the present passive technology appears to limit expected lifetime to 2 to 3 years. The totally passive system was adequate to obtain wide bandwidth records of small earthquakes (<M 5) for waveform analysis. Using a more sophisticated system, including downhole accelerometers (active sensors), would have been considerably more expensive and probably less reliable. The lower-frequency waves that could then be recorded are less affected by the near-surface conditions. Lower-frequency waves have longer wavelengths; for example, a P wave at 100 Hz has a wavelength of 50 m, whereas a P wave at 1 Hz has a wavelength of 5 km. The lower-frequency waves are therefore less affected by near-surface attenuation.

Acknowledgments

The sonde and cablehead were constructed at the University of Southern California machine shop. T. Henney and J. McRaney provided support and advice during the installation of the second phase. M. Robertson and A. Martin provided invaluable assistance with RefTek maintenance, and A. Martin also performed the geophone calibrations. IRIS, SCEC, and P. Davis (UCLA) provided RefTeKs for the recording. Tiger Wireline (Long Beach) performed both installations and the retrieval as well as advice as to the desirability of lowering two cables into one well, and they allowed us to use their premises for cablehead attachment. The USGS (J. Mori and B. Curtis) kindly provided us with burial barrels for the RefTeks to protect them from the weather and vandalism. J. Mori also provided us with the sample of noise at station JUL used in Figure 5. S. P. Passmore and D. Pavel (RefTek) generously designed and gave us an optically isolated triggering box to enable us to connect the three RefTeks together. We thank two anonymous reviewers for helpful suggestions. The borehole instruments were installed under NSF awards EAR-9004381 and EAR-9219856. Support was also provided by the Southern California Earthquake Center (SCEC). This is SCEC Contribution Number 208.

References


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