V007 BOREHOLE SEISMOLOGY — A HIGH RESOLUTION TECHNIQUE FOR AIDING DEVELOPMENT AND PRODUCTION

BJÖRN N.P. PAULSSON¹ and MICHAEL S. KING²

¹ Chevron Petroleum Technology Co., La Habra, USA

² Imperial College, Department of Earth Resources Engineering, Royal School of Mines, Prince Consort Road, London SW7 2BP, UK

Borehole seismology represents a rapidly developing technology for obtaining considerably better reservoir characterisation than that possible with the surface seismic techniques currently used. It is anticipated that borehole seismology will in the near future be used routinely for aiding in hydrocarbon development and production. For this purpose there are two different classes of application for borehole seismology: firstly, in monitoring and evaluating improved or enhanced hydrocarbon recovery processes, such as water or steam floods; and secondly, probably the more important, in reservoir characterisation for improved location of in-fill drilling or completion of new wells. Many problems associated with reservoir definition, such as in determining the continuity of bedding and the direction of fractures, in mapping lithology, fluid saturation fronts and fault planes, can be addressed using borehole seismology.

Oilfield seismology, which accounts for over 90 percent of all geophysical activities worldwide, has traditionally been applied from the surface of the earth. A number of advantages that result in better reservoir resolution, however, are achieved by placing the seismic source and receivers in boreholes. This has been demonstrated over the past ten years in a number of cross-well seismic surveys. The primary reasons for the superior performance of borehole seismic methods are:

- the absence of a weathered layer permits the use of seismic frequencies an order of magnitude higher than those possible using surface methods;
- the absence of the weathered layer makes it possible routinely to record high-quality polarised S-wave data;
- the recording environment is very quiet;
- both seismic source and receivers are close to the targets;
- the use of both direct and reflected P- and S-wave arrivals is possible.

The resolution and measurement lengths are indicated in Figure 1 for the common seismic techniques. The figure demonstrates that the new borehole seismic techniques provide a resolution and measurement length lying between those provided by surface seismic surveys and those provided by sonic logging. Figure 1 demonstrates also that only the borehole seismic techniques combine large measurement length with a resolution lying in the 1 to 5 m range.

Some applications of borehole seismic techniques in vertical and horizontal wells are shown in Figure 2. In the first application (cross-well seismology), two-dimensional velocity images may be constructed for the region between two or more wells using tomographic velocity imaging. Combining this velocity image with migration of cross-well reflections, it is possible to generate a seismic image with a resolution of between 1 to 2 m .

In the second and fourth applications (reverse VSP) shown in Figure 2, seismic energy is sent from the borehole to an array of geophones at the surface of the earth, or on the sea floor in the case of offshore wells. Experiments have demonstrated that much higher frequencies can be recorded in the reverse VSP configuration than in the conventional one.

In the third and fifth applications (single well seismic imaging) shown in Figure 2, the source and receiver array are placed in the same well. This technique lends itself ideally to mapping features at depth that are parallel or sub-parallel to the well. These applications of borehole seismology will provide seismic data of a quality previously unattainable.

An advanced borehole seismic data acquisition system has been developed by Chevron Petroleum Technology Company, in conjunction with the U.S. Department of Energy, E-Systems, Pelton, the Gas Research Institute, Exxon, Conoco and Amoco. The system consists of a powerful, clamped, swept-frequency, vibratory source which is non-destructive; a multi-level (100 levels) borehole receiver string of clamped, three-component geophones; and geophones and recording system for reverse VSP surveys. A prototype of the clamped seismic source has already demonstrated the ability to produce excellent high-frequency cross-well and reverse VSP data (Paulsson et al., 1994). The data

from this prototype source was found also to contain high-quality polarised direct S-wave arrivals, as well as P- and S-wave reflections.

The downhole seismic source and receiver array have been designed to meet the following specifications:

- High power. The power output must routinely achieve a seismic transmission distance of 1 000 to 2 000 m between wells or between a well and the surface. The vibrator has been designed to achieve this by clamping it to the inside of the well casing and hydraulically oscillating a heavy reaction mass. The generated peak force is 30 000 N over a broad frequency range.
- Non-destructive. The stresses induced by the clamped vibrating source must not damage the well casing or cement bond. The axial stress generated at the cement-casing bond will not exceed 170 kPa, which is well within the API recommended stress on this bond.
- Surveys in deep wells. The vibrator must be capable of operating in high-temperature, high-pressure and corrosive environments. It is designed to operate at temperatures to 200°C and at pressures to 80 MPa. The system is initially equipped with a 6500 m length electro-optical wireline.
- Broad frequency operation. High seismic frequencies (500 Hz to 1 kHz) are necessary to achieve a high resolution of small geologic images. Low seismic frequencies (10 to 100 Hz) are necessary when a reservoir contains free gas, because higher-frequency signals are attenuated. The vibrator has an effective bandwidth of 10 Hz to 1 kHz.
- Generate P and S waves in all directions. The first axial vibrator will generate P and S waves with polarisations parallel to the borehole axis. A full three-component seismic source that can generate P and S waves with polarisations both parallel and perpendicular to the borehole axis will be completed in 1997.
- Source and receivers in same borehole. The seismic source must not produce strong tube waves when performing single-well surveys to map features away from the borehole. This is achieved by clamping the source to the borehole wall. All seismic data are transmitted on fibre-optic communication channels contained in the electro-optical wireline, in order to

minimise electrical noise.

Reference:

Paulsson, B.N.P., Meredith, J.A., Wang, Z. and Fairborn, J.W. 1994. The Steepbank crosswell seismic project: Reservoir definition and evaluation of steamflood technology in Alberta tar sands, The Leading Edge, v.13, No. 7, 737-747.

Figure 1. Resolution and measurement length for different seismic techniques

Figure 2. Applications for downhole seismic vibrator