South Africa CO2 Seismic Program ANNEXURE B

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There have been great advances in seismic technology in the decades following the acquisition of legacy, limited-quality, 2D seismic profiles across the Zululand Basin. The South Africa government now plans to acquire new seismic data to determine if appropriate CO2 storage reservoirs are present in this onshore basin. The purpose of this document is to provide recommendations about equipment that should be used, and procedures that should be followed, in acquiring and processing these new seismic data.

The technical approach stressed in this document is structured around a long-ignored principle that vertical-displacement seismic sources (e.g. vertical vibrators) produce a robust, downgoing illuminating SV (shear wave) wavefield in addition to a downgoing P (compressional wave) illuminating wavefield. By integrating this important wave physics into a year-2017 seismic program, Zululand geology can be evaluated with both P-wave and SV-wave seismic data.

Seismic Data Acquisition

The initial stage of seismic data acquisition should involve regional 2D profiles positioned so that the resulting 2D images provide optimal information about the subsurface. This objective means that the profiles should pass across, or near, any existing drilled well in which subsurface geological information is available. South African scientists are in the best position to decide how to position these profiles based on known well locations and local cultural and environmental constraints. The optimal form of seismic imaging – 3D seismic data acquisition – will have to be delayed until a location is defined where a specific reservoir target needs to be evaluated in detail for possible CO2 storage.

Seismic Source

The optimal energy source for land-based seismic data acquisition is a vertical vibrator. Modern vibrators are not only powerful, but provide great versatility in creating illuminating seismic wavefields that are optimized for imaging specific targets. The vibrator used for the Zululand Basin seismic program should have a vehicle weight of approximately 60,000 lbs and be equipped with modern ground-force phase-locking electronics. A large-size vibrator means that only one vibrator will be needed at each source station to illuminate the moderate target depths (2000 m) that need to be investigated to evaluate Aptian reservoirs. Vibrators are typically operated so that they create a ground force that is 80-percent (or 70-percent) of the vehicle weight, which would be a ground force of 48,000-lb (or 42,000-lb) for a 60,000-lb vehicle.

Modern ground-force phase-locking electronics ensure that a consistent-shape imaging wavelet is produced at each source station regardless of the variable nature of soil stiffness coefficients along a seismic profile. Phase-locking electronics should be set so that the phase of each frequency component of an illuminating wavefield is not allowed to vary more than 5 degrees from the phase of the corresponding frequency component in the computer-stored master sweep. An example of vibrator performance when high-quality baseplate-control electronics are utilized on a 60,000-lb vibrator is exhibited in Figure 1. In this case, Pelton electronics were set so that ground-force phase-locking constrained all sweep frequencies to be within 3-degrees of the phase behavior of corresponding frequencies in the master sweep. Note the consistent ground-force magnitude applied by the baseplate during the complete 8-to-80 Hz, 10-sec sweep time when the drive level is set at 70-percent of vehicle weight (Figure 1a), and the constraining of the phase of each sweep frequency of this ground force to within 2-degrees of the frequency components of the master sweep signal (Figure 1b). These ground-force phase-locking data are digitally recorded and preserved for each vibrator sweep at each source station and are provided as a digital file to the client. An audible alert is sounded in the recording cab when a vibrator cannot maintain its phase-lock constraint so that the onsite vibrator mechanic instantly knows that a phase-lock problem has occurred. If phase-lock errors occur too often, the problem vibrator is taken offline, replaced with another vibrator, and then repaired, recalibrated, and parked offline until needed.

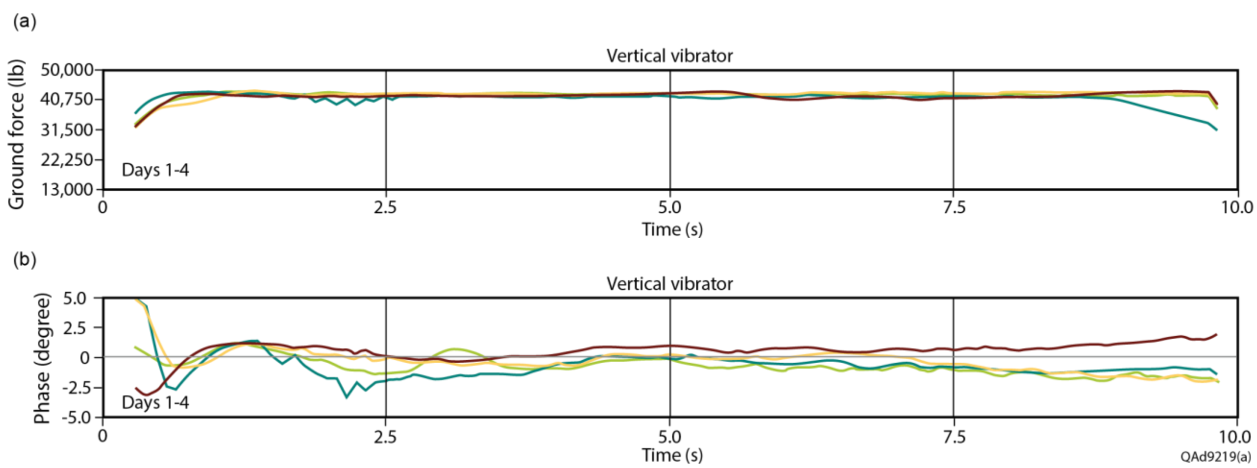

Figure 1. Ground-force phase-lock performance during a seismic data-acquisition program in west Texas. Each display has four curves that represent vibrator performance during 4 successive operating days. (a) Ground force magnitude when a 70-percent drive is utilized during an 8-to-80 Hz, 10-sec sweep. (b) Phase-lock at each of the 73 sweep frequencies stays within 2-degrees of the phase of the corresponding frequencies in the master sweep.

Key requirements for the vibrator sweep signal that creates illuminating wavelets along Zululand seismic profiles should be:

- Start frequency: The start frequency should be no higher than 4 Hz. It will be important to have strong low-frequency energy in the illuminating wavefield so that robust shear (SV) reflections will be created as well as strong compressional (P) reflections. Thus the start frequency must be as low as the seismic contractor will allow in order to avoid excessive mechanical problems in the vibrator fleet.

- Sweep rate: A linear sweep rate must be used. A non-linear sweep rate is not acceptable. The reason is again that the objective of this seismic program is to acquire SV-wave seismic information in addition to P-wave information. Linear sweep rates generate the robust low-frequencies that are needed for SV-wave imaging. In contrast, non-linear sweeps pass through lower frequencies fast and do not produce sufficient energy in the low-frequency range that is needed for optimal SV illumination of geology.

- Stop frequency: The stop frequency should be approximately 96 Hz. A 4-to-96 Hz sweep will cause the illuminating wavefield to span 4.5 octaves, which is a superb frequency span that will produce a compact, high-resolution imaging wavelet. A specific choice for the stop frequency can be determined by an onsite wave test done at the start of the seismic program.

- Sweep length: Long sweeps (20 sec or more) are preferred to short sweeps (10 or 12 sec). Summing two 20-sec sweeps tends to produce better data for combined P and SV imaging than does summing four or more shorter sweeps of 10 or 12 sec. Sweep length is another source parameter that can be determined by executing a pre-survey wave test.

- Listen time: 6 sec. Need to allow plenty of time to record SV-SV reflections from the deepest interfaces.

- Taper length: A 300-ms taper at the start/stop frequencies should be adequate.

The seismic contractor should have three identical vibrators onsite so that data production does not stop because of mechanical or electronic problems with one vibrator of the vibrator fleet.

Seismic Receivers

Single-point, 3-component, nodal receiver stations are mandatory. A cable-based data-acquisition system involves much more weight to transport and too many logistical and repair problems, particular if rats, rodents, and cattle are abundant along the seismic profiles. A receiver system that utilizes only single-component, vertical geophones allows only one SV mode to be utilized, this being the SV-to-P converted mode. It is much preferred that 3-component geophones be used so that all SV modes and all P-wave modes can be recorded.

The term ***single-point*** used to describe the desired receiver technology means that there should be only one geophone at each receiver station, not a string of geophones. The goal of this cutting-edge seismic data acquisition across the Zululand Basin is to utilize point sources and point receivers (hence a single heavy-weight vertical vibrator at each source station and a single geophone at each receiver station).

Figure 2. Representative single-point, nodal, receiver station. **GS-One** is a 3C geophone, and **GSR 4** is a 4-channel recorder and electronics package. The **Battery** dimensions are approximately 8-cm (width) and 25-cm (length).

A photo of a modern single-point receiver station is shown as Figure 2. The equipment shown in this figure is manufactured by Oyo Geospace, but equivalent equipment is made by other manufacturers. The equipment items in this photo represent a fully self-contained data-acquisition station consisting of a long-life battery (typically a 30-day to 60-day charge cycle), a single, strong-magnet, 3-component geophone, and an electronics package consisting of a digitizer, mass-storage memory, GPS, and precise internal clock. Typically GPS coordinates are calculated at short time intervals of 1 or 2 seconds, and the internal clock is rechecked at intervals of 10 seconds or less. Each receiver station can be programmed to prepare for data recording at a specified wake-up time and to cease operations at a specified go-to-sleep time.

Modern moving-coil geophones utilize powerful magnets that allow a single geophone to output a voltage equivalent to the voltage output of a string of 10 or 12 older geophones. An alternate form of receivers that would be acceptable would be receiver units that incorporate modern, 3-component, solid-state accelerometers.

Acquisition Geometry

This section specifies the desired dimensions of the intervals between successive source stations and receiver stations. These geometrical parameters control the quality of the data that will be acquired and also the cost of data acquisition. At this point, these parameters will be based only on conditions that ensure that the quality, information content, and value of the seismic data are maximized. When these acquisition parameters are discussed with potential seismic data-acquisition contractors, then budget factors may arise that require that these parameters need to be degraded.

Receiver-Station Spacing

The interval between successive receiver stations in the Zululand Basin seismic program should be 4 m. This distance is a short station spacing compared to what is usually practiced when acquiring seismic reflection data for imaging deep geology. The reason for a short distance between successive receiver stations is that it is important to record Rayleigh wave data that are appropriate for estimating the P-wave velocity (V_P) and the SV-wave velocity (V_S) in near-surface layers along each 2D seismic profile. The Rayleigh wave is a wave that propagates along the earth-air interface, does not illuminate deep geology, and is considered to be “noise” by most seismic data processers. However, Rayleigh wave data collected with small intervals between adjacent receiver stations are treasured by near-surface geophysicists and also now have great value in the new SV imaging technology that is being developed. The reasons why finely sampled Rayleigh wave data are needed are:

1. It will be important to estimate an important data-processing parameter called the *SV static*, which is a time shift that needs to be applied to data generated at each source station where a vertical vibrator creates a downgoing illuminating SV wavefield. This SV static can be determined from Rayleigh wave data only if the data are sampled at receiver stations that are closely spaced. A receiver station interval of 4-m will produce appropriately sampled Rayleigh wave data for estimating source-station SV-static corrections.

2. The collection of several hundred kilometers of 2D seismic profiles that have well-sampled Rayleigh wave data will be an invaluable database for near-surface studies that can evaluate water resources, or that investigate shear and compressional strengths of soils where construction projects may be considered, if such opportunities arise local to any of the Zululand 2D profiles in the future. This huge near-surface Rayleigh wave database that is proposed cannot be matched anywhere else on the globe and would be a research resource for countless South African students for years.

Swath Shooting

The term **swath shooting** refers to the procedure of recording 3, 5, or 7 parallel, closely spaced, 2D profiles centered on a 2D source line rather than recording only one receiver line. Some geophysicists refer to this procedure as 2.5D data acquisition because it is not 2D profiling but neither is it 3D data acquisition. The attraction of swath shooting is that it not only provides good-quality 2D profiles, but also provides information about cross-line structural dips.

There is a particularly important reason to perform swath shooting along the Zululand profiles – this being that swath shooting will allow SH (transverse-shear) data to be acquired in addition to the SV (radial-shear) data that have been discussed to this point. Material that describes how swath shooting provides the ability to integrate SH data into this Zululand Basin CO2 study is presented later in the data-processing discussion.

At this time, it will simply be stated that swath shooting is an important field data-acquisition geometry that should be implemented along each Zululand Basin profile. Specifically, my recommendation is that a geometry like that illustrated in Figure 3 be implemented. A minimum of 3 parallel receiver lines is required for swath shooting, which is the number of receiver lines used in this illustration. It is advantageous to deploy 5 or 7 parallel receiver lines if a sufficient number of nodal receiver stations is available to do so. Note the receiver-station interval of 4-m that is used. This small-interval station deployment ensures that there will be a proper spatial sampling of Rayleigh waves which will, in turn, allow V_P and V_S velocities to be accurately estimated in near-surface strata. A small source-station interval of 16-m is proposed to ensure that the processed data have a high stacking fold.

Seismic Data Processing

A vertical vibrator radiates downgoing illuminating P and SV displacements in a continuous, full-360-degree azimuth take-off range at each source station. A fundamental feature of upgoing SV reflections recorded by horizontal geophones distributed around a vertical-vibrator source station (or around any P-source station) is that the polarities of these SV reflections at negative-offset receiver stations are opposite to the polarities the same SV reflections have at positive-offset receiver stations. This principle is true whether upgoing SV reflections are created by a downgoing P wavefield or a downgoing SV wavefield produced by a P source. In order to process horizontal-geophone data, the polarities of positive-offset and negative-offset SV reflections must be identical. Otherwise any trace gathers that are constructed will have variable trace-to-trace reflection polarities, and the data cannot be converted into meaningful images. This SV polarity problem associated with all P sources is easily solved by reversing the polarities of all negative-offset traces at each P-source station so that the polarities of negative-offset and positive-offset data are identical, just as they are for a horizontal-vibrator source.

A map view of SV reflection polarities around a vertical-vibrator source station is like that shown by the four labeled arrows in the dashed circle of Figure 3. The X (inline) components of the hundreds of SV vector displacements that point in all azimuth directions at this source station can be summed into two vectors, **H_X(+)** and **H_X(-)**, that point in the positive-X and negative-X directions, respectively. These **H_X** components represent inline SV-shear polarities observed at every vertical-vibrator source station along the 2D profile. Similarly, the Y (crossline) components of the hundreds of SV vector displacements that radiate away from this vertical-vibrator source station in all possible azimuth directions can be summed to form two vectors, **H_Y(+)** and **H_Y(-)**, that point in the positive-Y and negative-Y directions, respectively. These **H_Y** components will be recorded by crossline horizontal geophones positioned along the three receiver lines and represent SH-shear polarities for 3C geophones distributed in the X-axis direction away from the source station. The full-azimuth SV radiation at a vertical-vibrator source station can thus be described by the four orthogonal **H_X(+), H_X(-), H_Y(+),** and **H_Y(-)** vectors drawn in Figure 3.

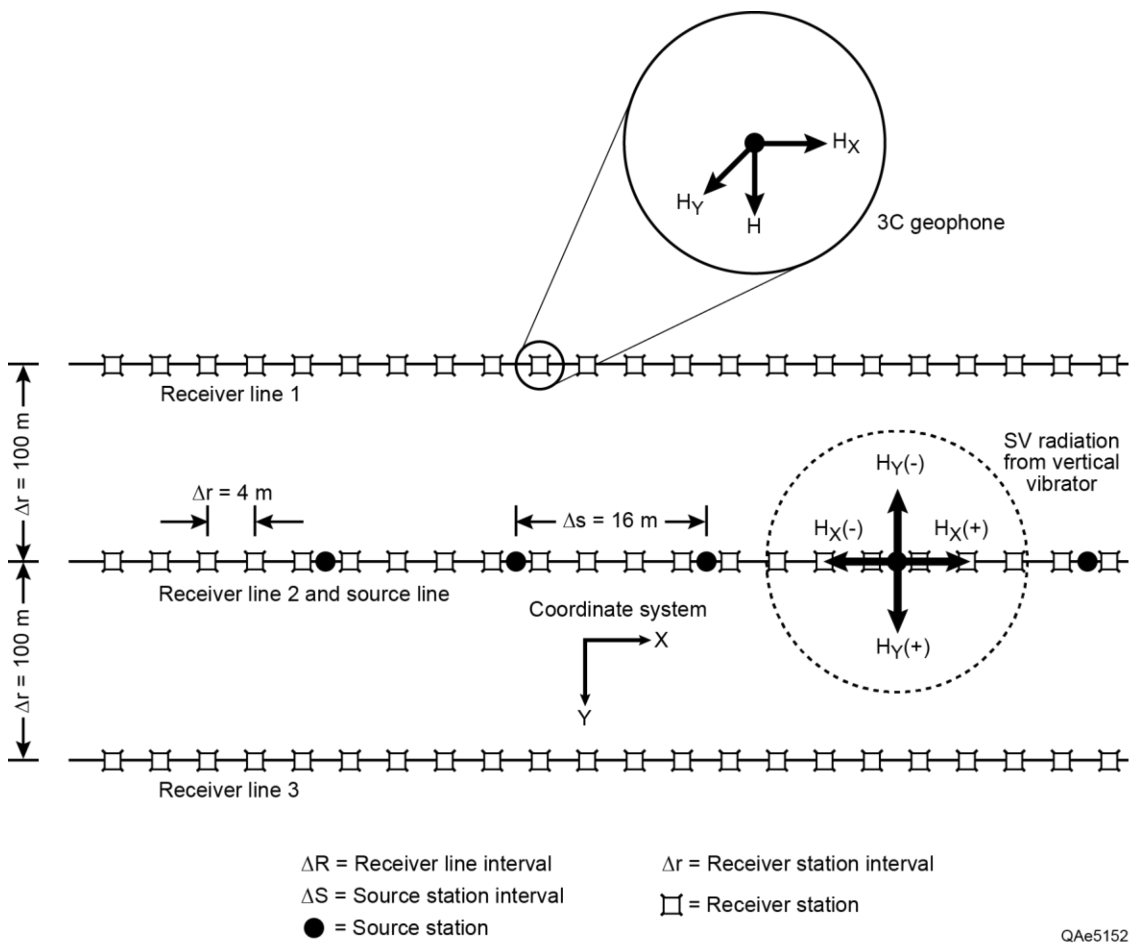

Figure 3. A map view of the type of swath-shooting geometry recommended for 2D profiles across the Zululand Basin.

For data generated at the source station in Figure 3 where the four **H_X(+), H_X(-), H_Y(+),** and **H_Y(-)** vectors are drawn, the polarities (algebraic signs) of all inline horizontal-geophone data recorded in the -X direction from the station only need to be reversed, which is the equivalent of reversing the direction of the **H_X(-)** vector to align with the direction of the **H_X(+)** vector. This simple polarity reversal of all negative-offset data from a source station causes all inline horizontal-geophone data along the full 2D profile to have consistent polarity, and SV reflection imaging can then be done in the same way that it is done with a horizontal-vibrator source.

It must be emphasized that this easy solution to maintaining consistent polarity of SV data recorded by inline-horizontal geophones is possible ONLY if receiver stations are positioned in both plus and minus directions from a source station. Thus inline (i.e. X-axis) SV data polarity can be managed during data processing because receivers exist in plus and minus inline directions from all source stations along a 2D profile. However, data polarity of crossline (i.e. Y-axis) **H_Y(+),** and **H_Y(-)** horizontal geophones cannot be managed if there is only one receiver profile because no receivers are positioned in plus and minus transverse (Y-axis) directions from the profile. Thus a 3-line receiver swath is drawn in Figure 3 so that there is a crossline horizontal geophone in both the plus and minus crossline (transverse) directions from each source station. With this 3-line swath acquisition geometry, data processors can create a consistent crossline (**H_Y**) data polarity which will allow SH (in addition to SV) imaging to be done along the X-axis profile. In some applications, SH-shear data have advantages that cannot be easily achieved with SV-shear data, and SH reflections should be acquired in the Zululand seismic program. Thus a 3-line swatch data-acquisition geometry is recommended for the Zululand Basin seismic program.

The author of this document (Bob Hardage) will be available to mentor any data-processing company who has not practiced full-elastic-wavefield imaging with P sources.

Receiver Inventory

The section view in Figure 4 shows the recommended data-recording strategy that should be used for the Zululand Basin and provides an insight into the receiver-station inventory that needs to be onsite to do the data acquisition. Two consecutive recording spreads are shown. The principal targets are Aptian sandstone units, which are placed at an approximate depth of 2000-m in this diagram, based on available well log data in the basin. Secondary targets are sandstones that are expected to be positioned at a depth of approximately 500-m, and a reflecting boundary is also indicated at that depth.

An active recording spread should extend a distance equal to (or greater than) the depth to the deepest target, thus receiver offsets extending from A to C are needed when a source station is at B, and receiver offsets extending from C to E are needed when a source station is at D. The A-to-C and C-to-E distances are each 4000-m (2 times the Aptian depth), which means there will be 2000 receiver stations extending from A to E if the recommended 4-m interval between successive receiver stations is honored. If a 3-line swath is used, as recommended, there will be 6000 receiver stations between coordinates A and E. For efficient data production, receivers need to be deployed that extend across four successive full spreads, not just two spreads as diagramed in Figure 4. Thus the selected seismic contractor should have an inventory of receiver equipment that will construct 12,000 or more receiver stations.

The signal-to-noise ratio, and hence the quality, of seismic images is proportional to the square root of the stacking fold that is created in constructing an image. If a 4-m interval is used for receiver stations and a 16-m interval is used for source stations (Figure 4), the stacking fold for Aptian targets (2000-m depth) will be approximately 250, and will be approximately 60 for secondary targets at a depth of 500-m. These stacking folds are huge compared to the stacking folds of 4 to 8 for Aptian targets that were used in the 1960's and 1970's to record legacy seismic profiles across the Zululand Basin.

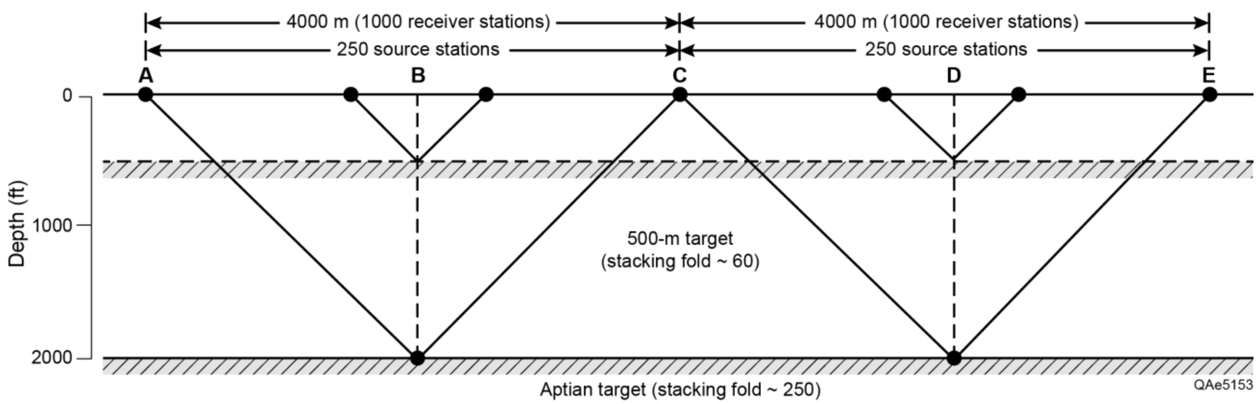

Figure 4. Section view of consecutive receiver spreads appropriate for imaging Aptian sandstones.