Multilevel Groundwater Monitoring with the Westbay System

Abstract

Understanding groundwater conditions for any purpose (such as characterizing a contaminant plume, managing groundwater resources, choosing a location for a geologic repository, investigating and remediating the stability of a complex rock slope, characterizing or monitoring a mine site, etc.) requires a three-dimensional array of measurement/sampling points. Historically, such an array has commonly been installed by placing a single access tube and inlet screen in each of a series of boreholes. With this method, the number of sampling points at a given site is generally limited by the high cost of drilling. A preferred alternative is to install monitoring points at many levels in each borehole (multilevel monitoring). Multilevel monitoring can provide increased data density and therefore a significantly improved understanding of site conditions. This paper describes how the Westbay* System, one type of multilevel monitoring system, is installed and operated. Field quality control procedures, 1) to verify the integrity of the access tube, inlet valves, and borehole seals, and 2) to confirm the operation of measuring and sampling equipment, are also discussed.

Introduction

When groundwater levels (pressures) and/or chemistry are suspected of varying vertically as well as laterally, a three-dimensional array of monitoring points is needed to identify significant variations and characterize the hydrogeologic conditions. In fact, such vertical variations are more often the norm than the exception and thus groundwater data must be obtained from a number of different locations and from a number of different depths at each location. As a result, either a large number of boreholes are required, each with a separate instrument installed, or instruments must be combined and installed at multiple levels in each of a smaller number of boreholes.

Multilevel groundwater monitoring devices have been described by many writers, some discussing the technical benefits and others the advantages to schedules and costs which can result when multilevel monitoring devices are used to reduce the number of boreholes required. Most important, however, are the advantages that accrue from the increased data density and from the field verification procedures that can be available. The very fact that one is capable of accessing several different discrete zones in one monitoring well provides an ability to 'view' and understand groundwater conditions in a way that is not otherwise possible. Further, if the multilevel system allows hydraulic testing (application of hydraulic stresses to one or more zones while observing the response of those zones and others), the system provides a testing and verification capability that is simply not possible in a single-level device such as a standpipe monitor well.

The basic requirements of any groundwater monitoring system are that it provide the user with the ability to measure fluid pressure, purge the monitoring zone, collect fluid samples, and undertake standard hydrogeologic tests, such as hydraulic conductivity tests and tracer tests. In addition, quality assurance plans for groundwater monitoring programs have led to a requirement for periodic testing and calibration of all aspects of groundwater monitoring devices.

Quality assurance plans normally require field verification tests immediately following installation and again at periodic intervals during the operating lifetime of the installation. In fact, few groundwater monitoring devices are designed to allow extensive field verification tests to be carried out. However, some types of multilevel monitoring instruments, such as the Westbay System, were designed with field verification tests in mind (Patton and Smith, 1986). With systems such as this, questions of data quality can be readily addressed.

General Description of the Westbay System

The Westbay System is a modular multilevel groundwater monitoring device employing a single, closed access tube with valved ports. The valved ports are used to provide access to several different levels of a borehole through a single well casing. The modular design permits as many monitoring zones as desired to be established in a borehole, within the limitation of the ability to fit the physical length of the components into the hole. In addition, at any time up to the moment of installation, zones may be added or modified without affecting other zones or significantly complicating the installation. As a result, the number and location of monitoring zones can be decided based on the information obtained during drilling. Only a broad scope of requirements need be defined in advance of drilling.

The Westbay System consists of casing components, which are permanently installed in the borehole, portable pressure measurement and sampling probes, and specialized tools. The casing components include casing sections of various lengths, regular couplings, two types of valved port couplings with different capabilities, and packers, which seal the annulus between the monitoring zones. The Westbay System has been used in many different geologic and climatic environments in boreholes ranging from a few feet to over 4,000 ft [1,200 m] in length. The 1.5-inch [38 mm] I.D. MP38 System has been used in the field since 1978, while the 2.25-inch [55 mm] I.D. MP55 System was developed in 1990-91.

Casing Components

The casing components of the MP38 System are made of plastic, while the MP55 System is available in either plastic or stainless steel. While the illustrations in this paper are of plastic components, the descriptions of operating principles that follow apply to both types of materials. Most of the components referred to are shown in Figures 1 and 2.

Casing

Westbay casing is supplied in a number of different lengths to provide flexibility in setting the position of monitoring zones and associated seals in the borehole. Common nominal casing lengths are 1 ft [0.3 m], 2 ft [0.6 m], 5 ft [1.5 m] and 10 ft [3.0 m]. The casing ends are machined to mate with Westbay System couplings incorporating a shear-rod connection and an o-ring seal.

Telescoping casing sections can be used to protect the casing string from damage when ground movements are anticipated or where measurements of axial displacements are desired.

Regular Couplings and End Caps

Regular couplings are used to connect casing lengths where valved couplings are not required. The couplings incorporate o-rings for a positive hydraulic seal. A flexible shear rod provides a tensile connection (no adhesives are used when joining casings and couplings). MP38 regular couplings incorporate an internal helical shoulder for the accurate location of probes and tools in the well. MP55 regular couplings do not incorporate a helical shoulder.

An end cap is placed on the bottom of each casing string. End caps also incorporate an O-ring seal so that the entire casing string is hydraulically sealed during installation. End caps are frequently used to seal the top of the Westbay casing between monitoring events.

Valved Couplings

There are two types of valved couplings: measurement ports and pumping ports. Measurement ports are used where pressure measurements (for water level) and fluid samples are required. In addition to the features of a regular coupling (plus the helical shoulder in the case of MP55), measurement ports incorporate a valve in the wall of the coupling, a leaf spring which normally holds the valve closed, and a cover plate which holds the spring in place. When the valve is opened, an access pathway is provided for the groundwater to enter the coupling.

Pumping ports are used where the injection or withdrawal of larger volumes of fluid is desired than would be reasonable through the relatively small measurement port valve (such as for purging or for hydraulic conductivity testing of moderate to high hydraulic conductivity materials). Pumping ports incorporate a sliding sleeve, sealed by o-rings, which can be moved to expose or cover slots that allow groundwater to pass through the wall of the coupling. A screen or slotted shroud is normally fastened around the coupling outside the slots.

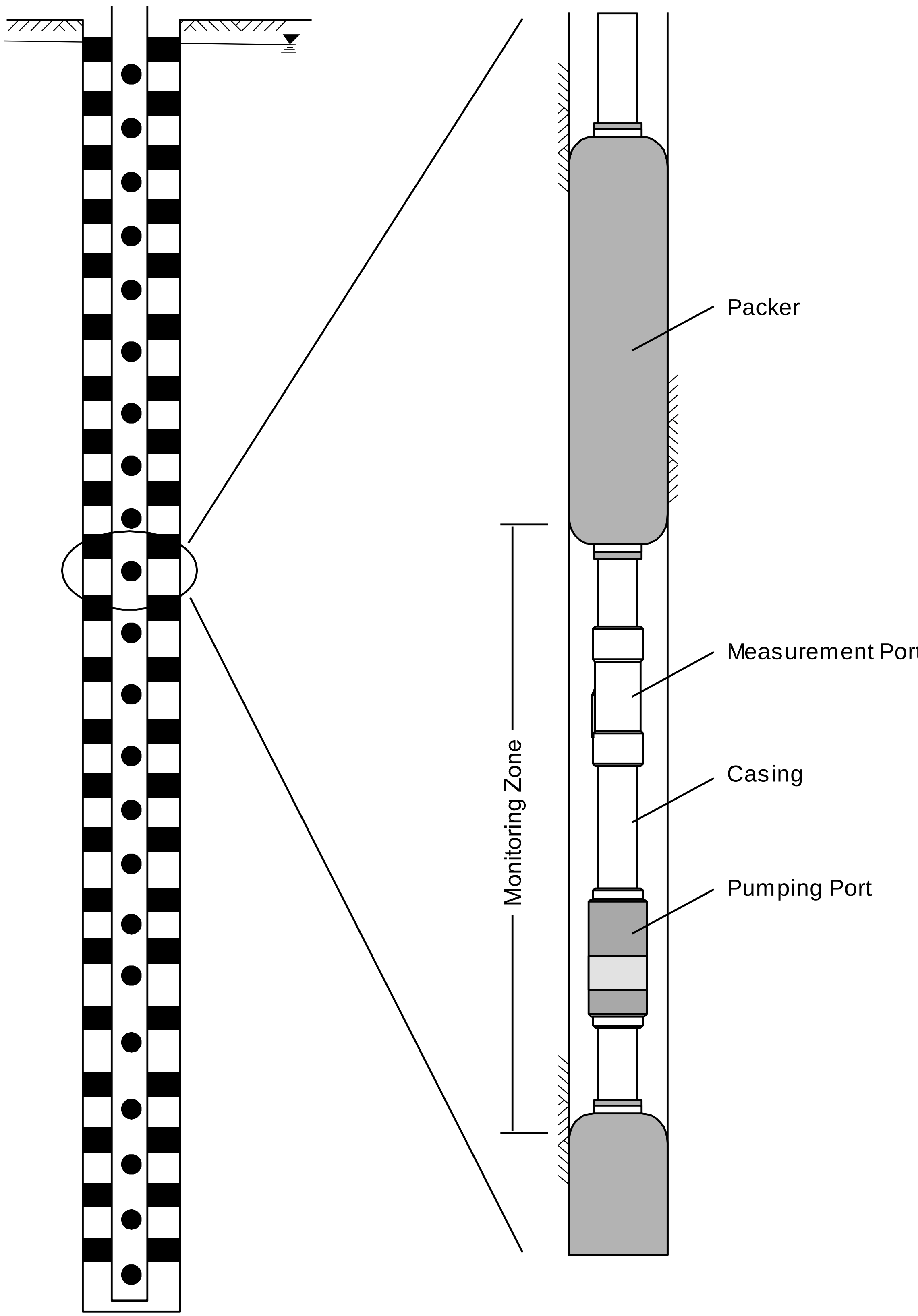


Figure 1. Westbay System with monitoring zones isolated by packers.

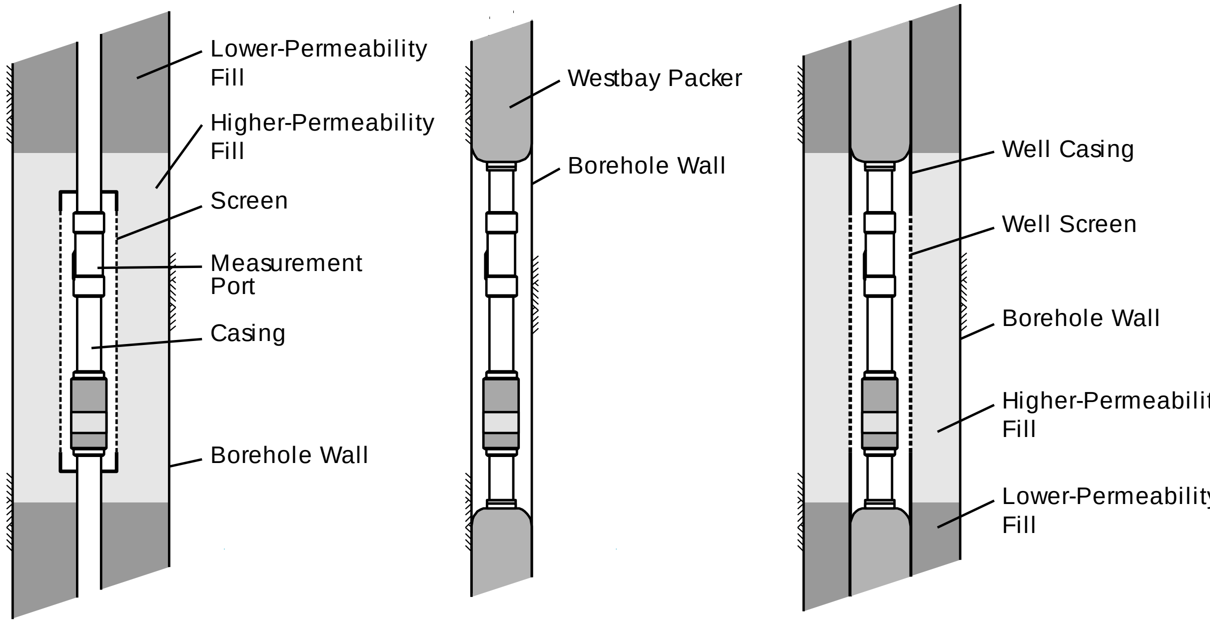


Figure 2. Common completion methods for the Westbay System.

Annulus Seals

When there are many monitoring zones in a single borehole, multiple seals are required to prevent fluid from flowing from one zone to another along the annular opening between the borehole wall and the casing. Placement of these seals can be difficult with any groundwater monitoring device. However, considerable success has been achieved with three types of well completion used with the Westbay System, provided each is combined with appropriate drilling and placement methods.

With the Westbay System, seals can be obtained by: a) backfilling with alternating layers of sand and bentonite or grout, b) using hydraulic (water) inflated packers or c) using packers inside a cased well with multiple screens. Figure 1 illustrates a borehole completed with the Westbay System with packers. Figure 2 illustrates a single measurement zone where the Westbay System is completed by each of the three common methods. Each sealing method is possible in most environments, but in many situations one method will stand out as the most advantageous.

Direct backfilling (Figure 2a) is recommended for: 1) large diameter boreholes, 2) shallow boreholes, 3) boreholes where little or no fluid circulation is anticipated in the hole during installation (i.e., when near-hydrostatic fluid pressures or low hydraulic conductivity is present over the length of the borehole), and d) where packer gland materials are incompatible with the chemistry of the fluids present.

When direct backfilling is considered and fluid sampling is required, a very clean drilling method must be employed. While the Westbay System does permit purging of monitoring zones, the small size of the casing prevents sufficient energy being generated to develop the monitoring zone.

Backfill seals may include bentonite and/or grout slurries, bentonite chips or pellets, bentonite/sand mixtures or other materials with a lower hydraulic conductivity than the natural formations present.

Westbay packers incorporate an expandable gland mounted over a standard length of Westbay casing. The casing incorporates a one-way valve that allows fluid to travel through the wall of the casing into the packer and prevents this fluid from flowing back out of the packer. Gland lengths are typically 3 ft [~1 m].

Packers in an open borehole (Figure 2b) are typically recommended for: 1) small diameter boreholes (where the annular space is too small for good quality backfilling to be achieved), 2) deep boreholes, and 3) sealing against significant flows within the borehole. When packers are used, field time for the installation is usually reduced since packer inflation is generally much faster than backfilling. When using more than one packer between primary monitoring zones, additional measurement ports are installed between the monitoring zones. Such additional ports provide additional (secondary) fluid pressure data that can be valuable for quality assurance (QA) purposes and for understanding the hydraulic characteristics of the site.

Packers in a cased well (Figure 2c) is a completion method that has proven very successful for environments where available hole sizes are too large for packers and/or where drilling additives, such as mud, must be used for borehole support. This completion method involves drilling a large diameter hole, typically 12-inch [300 mm] and installing well casing with multiple screens (typically 4-inch [100 mm] nominal diameter for MP38 and 5- or 6-inch for MP55). The well screens are located at all of the desired monitoring levels, based on information gathered during and following drilling. Layers of select backfill material are placed to provide filters around the well screens and annular seals between. Each monitoring zone is then thoroughly developed through the well casing. Following development, Westbay casing, ports and packers are installed inside the well casing. The Westbay packers are inflated against the inside of the well casing, providing interior annular seals between the monitoring zones. This completion method provides the ability to properly develop mud from deep mud-rotary boreholes, as well as to service the Westbay System during the operating life of the monitoring well. When more than one packer is installed between adjacent well screens, additional measurement ports are installed between the monitoring zones for QA purposes. Measurements and tests carried out through these additional "QA ports" can enable easy evaluation of the effectiveness of the packer seals at any time throughout the operating life of the installation.

Screens and Filters

Where both pumping ports and measurement ports are being used and the ports are likely to be surrounded by sand fill or collapsed geologic material, a single well screen may be placed over both the measurement port and pumping port in each monitoring zone as shown in Figure 2a. The screen helps the zone influenced by pumping through a pumping port extend to and include the region surrounding the adjacent measurement port coupling. Screen slot size and length should be chosen based on a knowledge of local site conditions. If only fluid pressure measurements are required, a simpler fabric filter tube can be placed over the measurement port coupling and fastened at either end. This filter will help maintain the length of the monitoring zone and protect the measurement port valve from fine particles. The filter material should be compatible with the chemistry of fluids present.

Magnetic Location Collars

A magnetic location collar is a plastic collar containing a circular array of magnets. When the collar is installed around the Westbay casing, a magnetic field is established across the axis of the casing. Probes and tools lowered into the casing can detect this magnetic field and transmit a signal to the operator, confirming the depth of location of the probe or tool. Magnetic location collars are installed at specific locations during the assembly of the Westbay System at the monitoring well and are held in place by a stainless steel clamp.

Installation Procedures

Selection of Casing Components

The valved couplings (measurement ports and pumping ports) allow many monitoring zones to be established in a single borehole. Horizons of hydrogeological interest are targeted on the basis of the best borehole geologic and geophysical logs available. An installation log is prepared showing the locations of the casing components. If only fluid pressures are needed, only a measurement port coupling is required in each monitoring zone. If sampling and/or hydraulic testing (i.e., fluid withdrawal or fluid injection) is anticipated, both a pumping port and a measurement port are recommended in each monitoring zone. This is the case illustrated in Figures 1 and 2.

The casing lengths are chosen based on the desired locations of the monitoring zones and sealing elements. This requires an interpretation of the hydrogeologic conditions anticipated in each borehole. Caliper logs and borehole video can be useful when selecting packer locations.

If movement is expected along the borehole axis (i.e., consolidation or heave), telescoping casing sections may be used to minimize the opportunity for compressional or tensile forces to damage the casing.

Westbay Casing Installation

The downhole Westbay System components - casing, couplings and packers- are laid out at the site of the proposed monitoring well in accordance with the casing installation log. At that time, any last minute adjustments required to make the positions of the monitoring zones and seals match hydrogeologic details of the borehole are completed and the appropriate revisions are made to the installation log.

Next, the required coupling is attached to the top of each length of casing. The casing layout is checked again for compliance with the installation log. Serial numbers of measurement ports, pumping ports and packers are recorded, indicating their position on the installation log. The length of all casing sections is measured and recorded on the log.

The casing string is then assembled by lowering the casing segments into the borehole and attaching each successive segment to the adjacent coupling one at a time. As each successive Westbay casing section is attached to the string in the well, the section number is checked and recorded on the installation log. The coupling joint is then subjected to an internal hydraulic pressure to verify its hydraulic integrity and the test result is recorded on the log. This is an important step in confirming that the system is sealed to prevent cross-contamination. Because the Westbay casing is sealed along its entire length, as the casing is lowered into water in the borehole, it will become buoyant. At intervals during lowering, clean water is added to the inside of the Westbay casing to reduce its buoyancy.

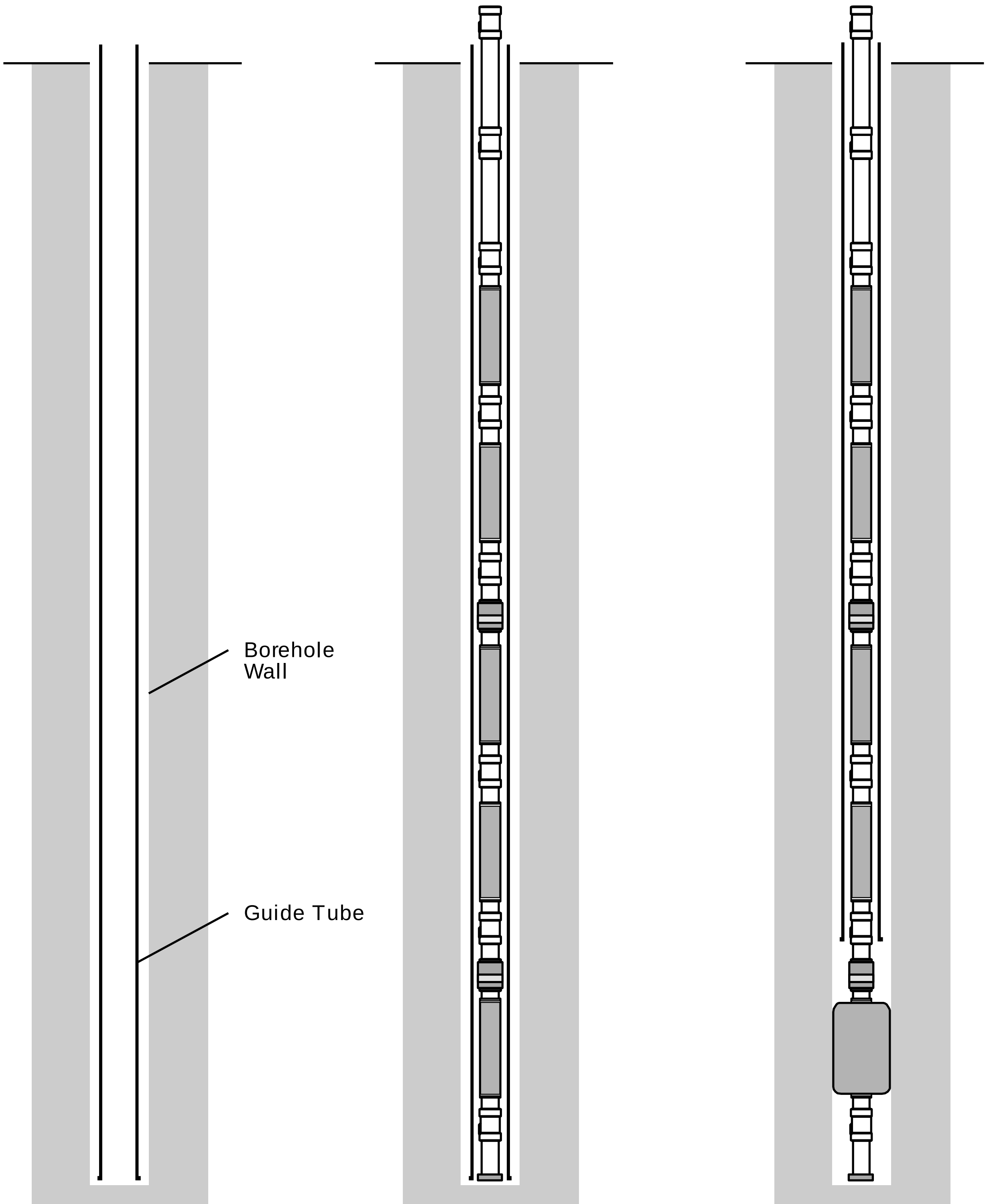
In collapsing soil and poor quality rock, Westbay casing with packers and screens may be installed through a temporary flush-jointed guide tube such as drill rods or casing. Table 1 provides ranges of borehole, casing and guide tube sizes for the MP38 and MP55 Systems. Figure 3 illustrates the major stages of installing through a guide tube: 3a) Following completion of drilling, the guide tube is positioned in the hole. All parts of the guide tube, including any shoe attached to the bottom, must be flush on the interior and of sufficient inside diameter to permit the Westbay components to pass through; 3b) The Westbay components are assembled and lowered into the guide tube in such a fashion that the packers and ports will be correctly positioned in the hole when the bottom of the Westbay casing is resting on the bottom of the borehole; c) The guide tube is pulled back to expose a packer and that packer is inflated. The pulling/inflating sequence is repeated until all of the packers have been inflated. More than one packer may be exposed during each pull of the guide tube, depending upon the stability of the borehole walls. If the Westbay casing does not extend to the bottom of the borehole, a sufficient number of packers must extend below the guide tube such that they can be inflated to support the weight of the Westbay casing and hold the assembly in the correct position before the guide tube can be removed.

System	I.D.		Max. Depth[1]		Borehole/Casing Size		Min. Guide Tube I.D.	
	in.	mm	ft	m	in.	Mm	in.	mm
Plastic MP38	1.5	38	4,000	1,200	3-6.25	75-160	3	75
Plastic MP55	2.25	55	4,000	1,200	4-6.25	100-160	4.75	120
Steel MP55	2.25	55	7,000	2,100	4-9.4	100-240	4	100

[1] Note: Maximum depth can vary case-by-case. Please consult Westbay technical support.

Table 1. Important dimensions for the Westbay System

Casing without packers can be placed in various sizes of boreholes, with or without protective casing, as long as the borehole diameter (and casing) is compatible with the backfilling method.



a) Hole drilled, guide tube
in place

b) Westbay casing lowered
inside guide tube

c) Guide tube pulled bac
packer inflated.

Figure 3. Installation of Westbay System through a temporary guide tube.

Good backfilling techniques involve the use of one or more tremmie pipes and frequent sounding to confirm the depth of the backfill materials.

Once the Westbay casing has been placed in the borehole, the packers are inflated (see Figure 3) or backfill is placed. If the Westbay casing was lowered inside a guide tube, the guide tube may be withdrawn all at once or in steps as the packer inflation or backfilling operation proceeds. Incremental withdrawal of the guide tube can reduce the opportunity for the borehole wall to loosen and cave prior to the placement of seals.

Packer Inflation

Figure 4a shows the appearance of a casing packer when it has been placed in a borehole before inflation. Figure 4b shows how the MP38 System casing packers are individually inflated using a packer inflation tool. This tool is lowered down the inside of the Westbay casing and is located in the correct position by the location arm seating in the coupling directly beneath the packer.

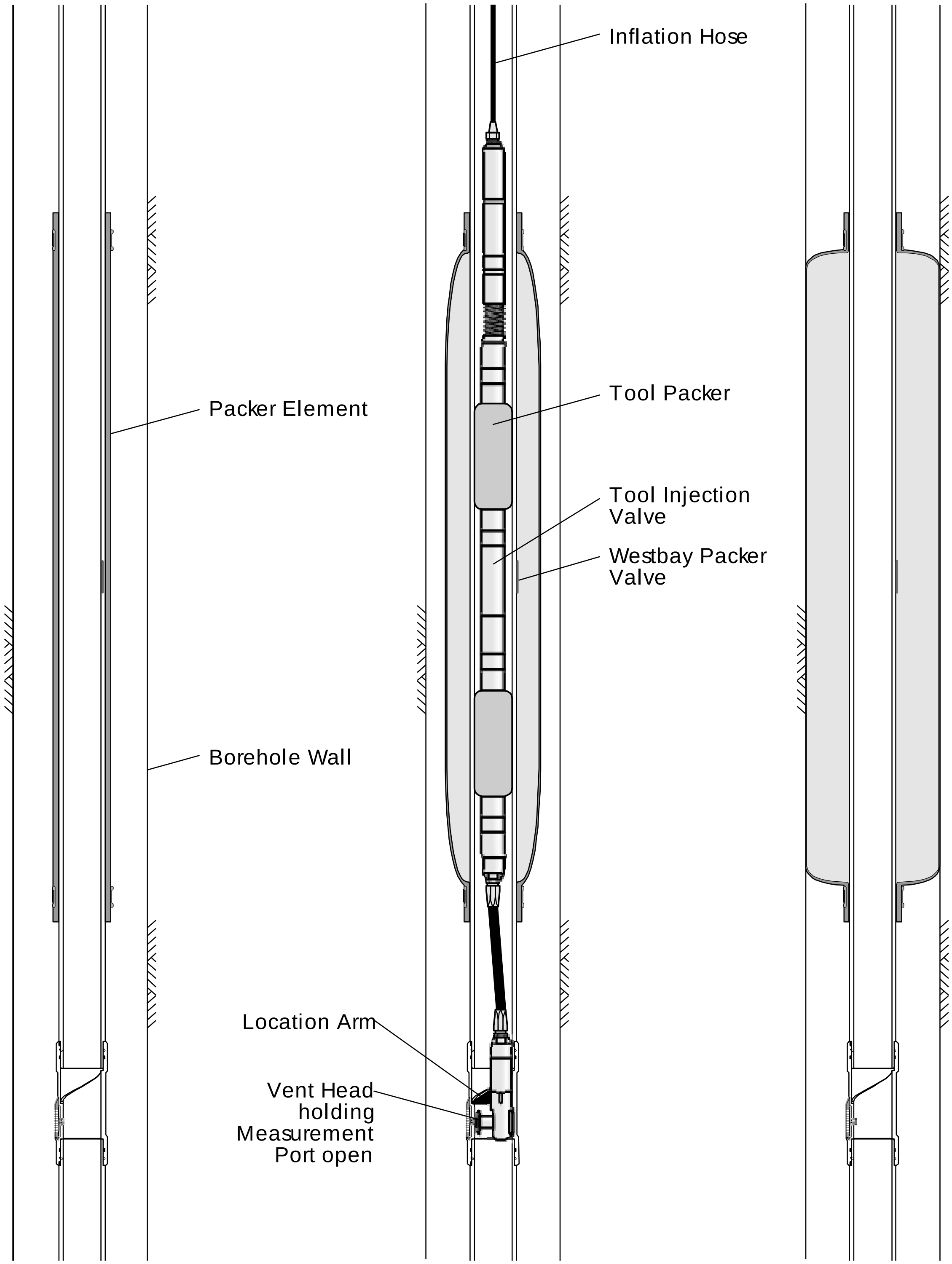
Two small packers (inflation tool packers) are inflated, isolating the short segment of the casing containing the valve for the casing packer. At a pre-set pressure, the tool injection valve opens and water is injected into the casing packer. If a measurement port is installed directly beneath the packer, the vent-head mechanism on the tool holds the measurement port open during inflation. This vents the pressure in the zone below the packer, allowing the packer to square-off without generating unnatural squeeze pressures. Figure 4c shows the inflated Westbay packer after the inflation tool has been removed. At increments of volume during the inflation process, pumping is stopped and the fluid pressure of the inflation system is measured and recorded. The pressure/volume data is plotted and kept for quality assurance purposes.

Packer inflation proceeds from the bottom of the hole to the top. There are no permanent inflation lines leading to each packer. As a result, there is no limit to the number of packers that can be placed in a borehole apart from the finite limitations of packer length and borehole length.

Purging Monitoring Zones

If purging is required following installation, the strategy for purging the monitoring zones may vary depending on site conditions. Once the casing and annular seals have been installed, it is usually desirable to remove the non-representative fluid trapped in the various zones during installation. This removal, or purging, can be done in one of two basic ways: 1) Purging by natural groundwater flow, or 2) Pumping to purge monitoring zones.

Purging by natural groundwater flow is attractive, particularly in environments where groundwater flow is understood to be relatively rapid. In such an environment, unnatural fluids introduced during drilling while the borehole was open may no longer be adjacent to the borehole by the time the monitoring system has been installed. In such a case, there may be little to be gained from the investment of time and resources to pumping an arbitrary volume of water from each monitoring zone. Rather, fluid samples might be collected over a period of time and



a) Westbay Packer as installed.

b) Inflation tool inflating packer.

c) Packer inflated, too removed.

Figure 4. Steps in the inflation of a Westbay System packer.

analytical results compared in order to evaluate the stabilization of conditions in the monitoring zone.

When purging by natural flow is not acceptable, monitoring zones can be purged by pumping. Zones are typically pumped one-at-a-time to prevent cross-contamination. Individual hydrogeologists and hydrochemists may prefer different purging techniques depending upon local conditions. However, the purging procedures are essentially the same as would be used for a single standpipe piezometer. One procedure which has been successfully used is described below.

1. An acceptable and convenient tracer is added to the drill fluid during drilling.

2. After the casing has been installed and the packers have been inflated, an open/close tool is used to open the pumping port in one of the monitoring zones. With one pumping port open, the Westbay casing is hydraulically identical to a standpipe piezometer with its screen located at the same depth as the open pumping port.

3. Fluid from the inside of the Westbay casing is pumped out of the well. Either a set quantity of fluid may be pumped from inside the Westbay casing or pumping is conducted until some desired condition is met to complete the purging of this monitoring zone. Hydrogeologic testing of this zone and its adjacent casing seals can be done at this time. For example, slug tests can be undertaken to obtain hydraulic conductivity. The volume of fluid removed and the pumping time for purging will depend on many factors including: the drilling method, the length of time the hole was left open prior to completion, the hydrogeological conditions in the borehole, etc. The use of a tracer can be helpful in determining when the purging is completed.

4. Once purging of one zone has been completed, the open/close tool is used to close the pumping port, another pumping port is opened, and the process is repeated.

5. Once all desired zones have been purged, and the last pumping port is closed is closed, the interior of the Westbay System may be flushed with clean water and the water level adjusted as meets the specific needs of the project.

Following purging, the Westbay System is ready for sampling, pressure measurements, and further testing.

Operation of the Pumping Ports

To operate a mechanical pumping port, an open/close tool is used as illustrated in Figure 5. This tool has spring-loaded "jaws" which can be mechanically activated from the surface. The pumping port is shown closed in Figure 5a. To open the valve, the tool is lowered on a wireline with the jaws extended and pointing upward (i.e., so that they will catch on shoulders when the tool is raised). In this condition, the jaws will spring through each coupling as the tool is lowered

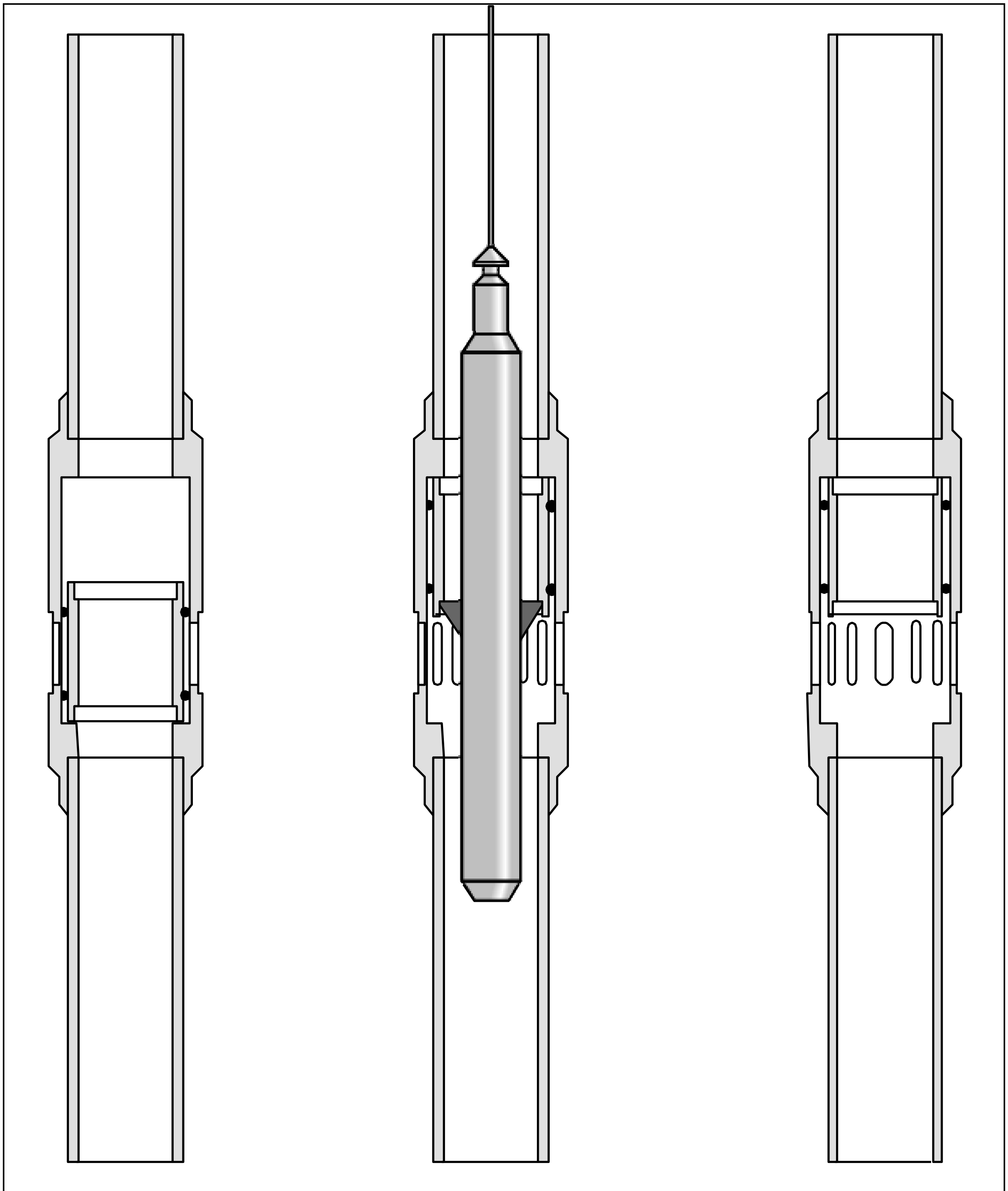


Figure 5. Operation of a Westbay mechanical pumping port.

to just below the desired pumping port coupling. The open/close tool incorporates a sensor to detect magnetic location collars and confirm the location of the tool in the well.

Once located in the desired pumping port, the open/close tool is pulled up so that the jaws engage the bottom shoulder of the sliding valve. By continuing to pull up on the wireline, the valve can be opened, as in Figure 5b. Once the valve is opened, the jaws can be collapsed into the housing and the tool recovered. With this one valve opened, fluids can be added to or removed from the monitoring interval by injecting into or pumping from the Westbay casing. Other zones may still be monitored in the normal manner using a pressure probe or sampling probe as they will not be hydraulically connected to the interior of the casing.

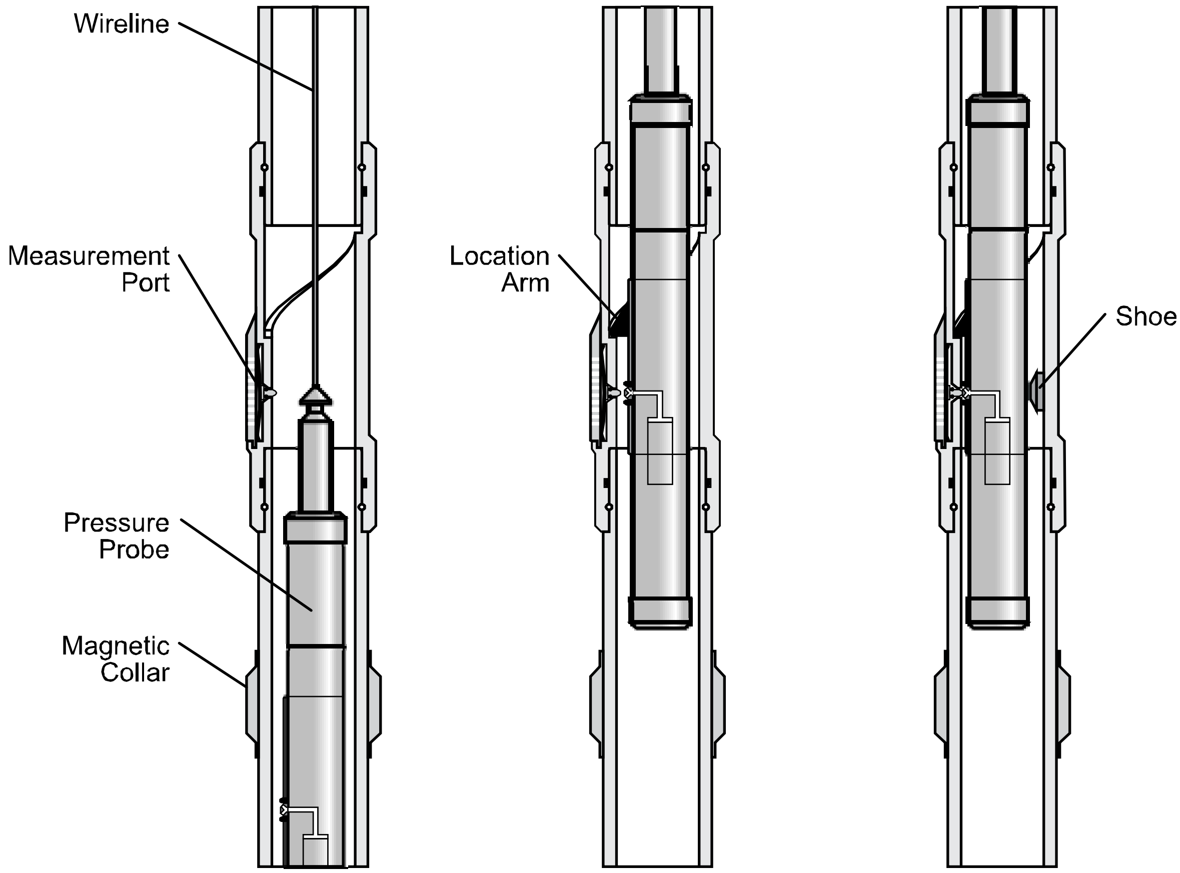
To close the pumping port coupling, the open/close tool is brought to the surface and the housing is reversed so that the jaws point downward (i.e., the tool will stop on exposed shoulders when the tool is lowered). The tool is lowered to the open pumping port with the jaws retracted into the housing. Once the tool is located near the pumping port, the jaws are released and the valve is closed by tapping on the top shoulder of the sliding valve with the tool.

Testing and Monitoring

Fluid Pressure Measurements

Fluid pressure measurements can be made at each location in a borehole where a Westbay measurement port has been installed. The measurement port incorporates a helical landing ring and a leaf spring valve which is normally closed. The fluid pressure is measured using a pressure probe or sampler probe which incorporates a location arm, a shoe, a face seal, and a fluid pressure transducer. These features are shown on Figure 6. The probe is operated on a wireline cable connected to an interface and (optional) portable computer at the top of the monitoring well. The interface displays the pressure and transducer temperature digitally plus some probe status information, while the computer displays the pressure both graphically and digitally, along with transducer temperature, well information and probe status.

The following procedure is used to make fluid pressure measurements. The probe is lowered to a point below the first measurement port to be accessed (usually the deepest) (Figure 6a). If a magnetic location collar has been installed near this port, the probe detects the magnetic field and transmits a signal to the interface where an audible tone is emitted, confirming the probe's location for the operator. The location arm is released from within the probe body. The probe is raised to just above the measurement port coupling and then lowered until the location arm rests on the helical landing ring in the coupling. The weight of the probe causes it to rotate into position at the correct depth and orientation to operate the valve (Figure 6b). At this point the pressure transducer is measuring the fluid pressure inside the Westbay casing at that depth. This reading will be displayed on the surface interface or computer and is recorded.



a) Probe detects magnetic collar. Transducer measures pressure inside Westbay casing.

b) Location arm is released and probe lifted to locate in measurement port. Transducer measures pressure inside Westbay casing.

c) Shoe extends, sealing probe around measurement port while opening port. Transducer measures pressure outside Westbay casing.

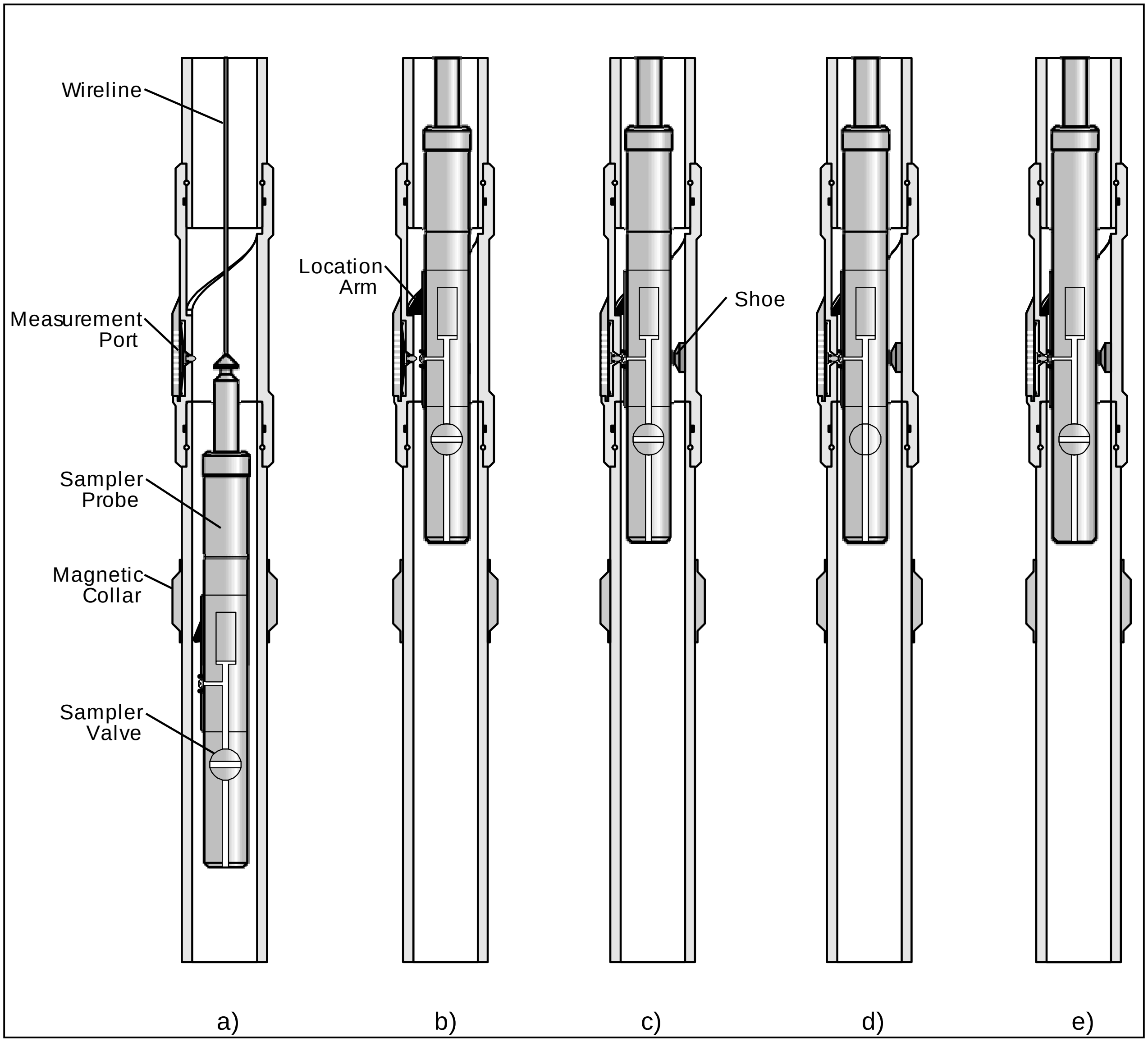
Figure 6. Operation of a pressure probe.

The shoe is then activated. It extends and pushes the probe against the wall of the measurement port so that the face seal on the probe seals around the measurement port valve at the same time as the face of the probe pushes the valve open. The transducer is now hydraulically connected to the fluid outside the port and isolated from the fluid inside the casing (Figure 6c). The reading displayed on the interface or surface computer will be the absolute fluid pressure in the formation outside the measurement port. The pressure outside the port can be observed as long as desired and recorded as often as desired. After the reading has been recorded, the probe shoe is retracted and the valve in the port reseals. The probe will again be measuring the fluid pressure inside the Westbay casing (Figure 6b). The pressure in the casing is again recorded, for quality assurance purposes. The probe may then be moved to another port or removed from the well.

Measuring Pressure in Low Permeability Environments

Very low permeability environments present a special challenge for measuring fluid pressures. When the routine profiling procedures described above are followed, a stable pressure may be observed through the measurement port. However, the act of opening the port may be sufficient to change the pressure in the monitoring zone, and if the zone is very tight, that pressure change may not dissipate quickly enough to be observed. In such an environment it is always difficult to determine the validity of a single manual measurement unless some form of dynamic test is carried out as well. In the case of the Westbay System, this is done through the use of a sampler probe. As illustrated in Figure 7a), the sampler incorporates all of the features of a pressure probe, plus a valved passage which is controlled via the surface interface or computer. With the

Figure 7. Using a sampler probe for testing hydraulic conductivity and verifying fluid pressure



measurements in low-permeability environments.

sampling valve closed the probe acts identically to a pressure probe and thus may be used for single-probe profiling. The difference is that once the probe is located and activated (Figure 7c), the fluid level inside the Westbay casing may be adjusted to a level slightly higher or lower than the piezometric level in the monitoring zone. The sampling valve can then be opened (Figure 7d), exposing the monitoring zone to the fluid pressure in the Westbay casing. In very low permeability environments, no water will flow during this time. The sampling valve may be kept open for a specified period of time (such as one minute). The sampling valve is then closed (Figure 7e) and the pressure recovery in the monitoring zone is recorded vs. time (Figure 8). Standard analytical methods can be applied to the pressure recovery data in order to determine the apparent pressure in the monitoring zone. The same procedure can be used for testing hydraulic conductivity in low-k zones. When groundwater does flow in through the sampler during such a test, the flow volume can be calculated by measuring the change in water level inside the Westbay casing, or by capturing the flow in a sample container.

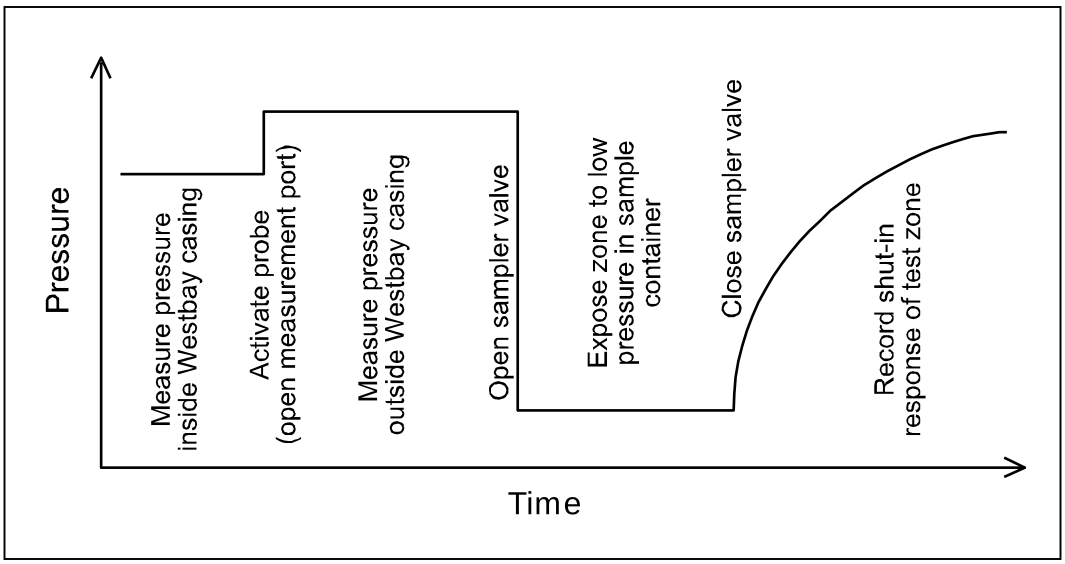


Figure 8. Typical data record from a test in a low-permeability zone using a sampler probe.

Pressure Monitoring Methods

The two principle methods of monitoring fluid pressure with the Westbay System are illustrated in Figure 9. Single-probe profiling (Figure 9a) involves an operator traveling to each well with a set of portable equipment including a pressure probe, cable and reel, interface and computer. The operator manually locates the probe at each measurement port and carries out fluid pressure measurements one at a time. When a computer is used, the MProfile software stores the data on disk with each record tagged as to the location of the probe in the well, date, time, and probe status. If the interface is used alone, measurements may be recorded manually. Single-probe profiling is generally adequate for monitoring fluid pressure up to a frequency of once per month.

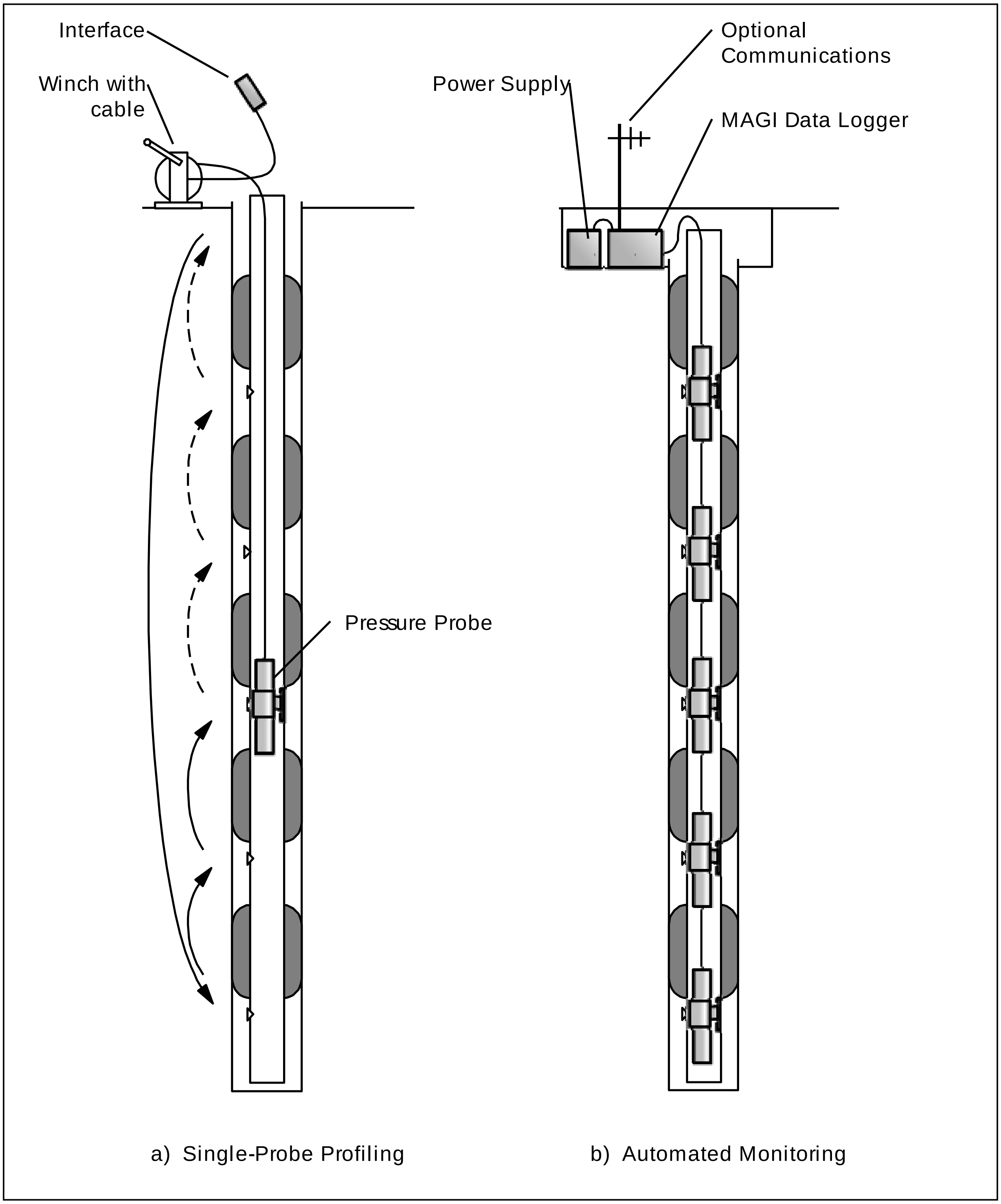


Figure 9. Schematic illustration of methods of monitoring fluid pressure with the Westbay Sy:

When pressure measurements are desired more frequently than is reasonable for single-probe profiling, continual observation and recording of unanticipated events is required, or site access is difficult, the monitoring well can be configured for automated monitoring (Figure 9b). Any or all of the measurement ports in a well may be selected for automated monitoring. Lengths of cable are made up to span the distance between each probe and the next. The string of probes and cable is assembled and lowered into the well. The data logger and a computer running Westbay MLog software are attached at the surface and the lowermost probe is located and activated in the appropriate measurement port. The remaining probes are located and activated sequentially from the bottom of the well to the top.

Once all of the probes are activated, the computer is used to program the data logger. Pressure measurements may be recorded on a simple time basis (e.g., one reading per minute, hour or day, etc.), or the logger may be programmed to continually scan each probe and record pressures only if a specific threshold pressure change is exceeded. Each probe may be assigned an independent threshold (i.e., record data if Probe 1's reading changes by 5 ft of water, Probe 2 by 15 ft, etc.).

The data logger may stand unattended, in which case an operator would periodically visit the site to download the stored data, or the data logger may be connected to a telemetry system such as an RF modem, cellular system, or landline. When connected to a communication device, a second threshold can be designated for each probe which will cause the logger to transmit an alarm signal to the host computer. The host computer can also run a program to automatically connect with each data logger on a set schedule, download the newly-acquired data, convert the data files for use, store them on the specified server, and produce a report on the data obtained, instrument status, etc.

A unique aspect of monitoring with the Westbay System is that unusual pressure readings can often be verified by means of an in-situ calibration check. When an alarm condition is received, a natural first reaction would be to question the validity of the measurement ("Is it real, or is it the instrument?"). When datalogging with the Westbay System, if an alarm is received, the operator can log onto the well via remote communications, deactivate two or more probes including the one causing the alarm and compare their measurements of the fluid pressure within the Westbay casing. The column of fluid inside the Westbay casing is independent of all of the monitoring zones and thus serves as a reference pressure source. If the deactivated probes agree on the internal water level, the alarm condition can be taken to be valid and the probes can be reactivated to resume monitoring. If the probe causing the alarm did not agree with the others, instrument error might be suspected. In such a case, an operator could visit the well, remove the string of probes, replace the offending probe and reinstall the string to resume monitoring. The offending probe could then be calibrated and serviced in a laboratory.

Fluid Sampling

Fluid samples are obtained by lowering a sampling probe and sample container(s) to the desired measurement port coupling. As shown on Figure 10, the sampling probe operates in similar fashion to the pressure probe except that a groundwater sample is drawn through the measurement port coupling. Whenever the sampling probe is operated with the sampling valve closed, it is identical to a pressure probe and supplies the same data.

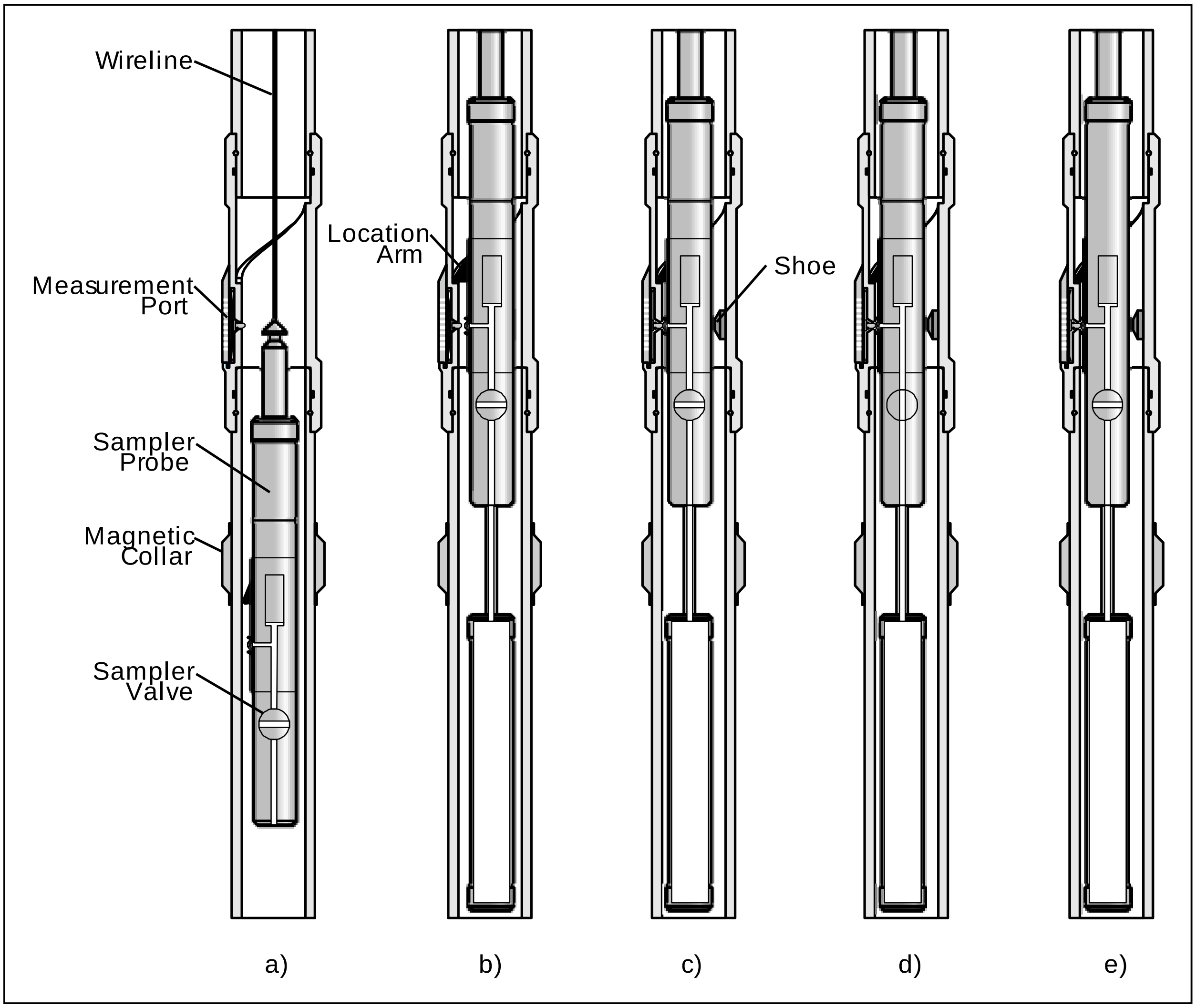


Figure 10. Operation of a Westbay sampler probe.

The procedure for collecting a groundwater sample is as follows:

A clean, empty sample container is attached to the sampling probe. The probe and container are prepared (e.g., cleaned and often evacuated) in a manner suited to the specific project and the sampling valve is closed to prevent the fluid inside the Westbay casing from entering the sample container. The probe and container are lowered to below the selected measurement port coupling. If a magnetic collar is present, the probe detects the magnetic field, confirming the location of the probe (Figure 10a). The location arm is released, the probe is positioned in the measurement port coupling and the fluid pressure inside the Westbay casing is recorded (Figure 10b).

The probe shoe is activated and pushes the probe against the wall of the coupling so that the face seal on the probe seals around the measurement port valve at the same time as the face of the probe pushes the valve open. The interior passage of the probe is now hydraulically connected to the fluid outside the coupling (Figure 10c), but no fluid movement takes place. During this operation the change in fluid pressure is observed at the surface and may be recorded.

The sampling valve in the probe is opened, allowing fluid from outside the measurement port to flow through the probe and enter the sample container (Figure 10d). The pressure displayed at ground surface drops and then recovers as the fluid in the container builds to formation pressure. Once the container is full, the sampling valve is closed (Figure 10e). The shoe is retracted (Figure 10b) and the fluid pressure inside the Westbay casing is once again recorded. The sampling probe and sample container are then pulled to the surface. The sample is typically transferred to alternate containers for transport and analysis, then the sampling probe and container(s) can be cleaned and the procedure repeated.

When using the standard non-vented sample container, the fluid sample is maintained at formation pressure while the probe and container are returned to the top of the well. Once recovered, there are a variety of methods of handling the sample:

- the sample may be depressurized and decanted into alternate containers for storage and transport,

- the sample container may be sealed and transported to a laboratory with the fluid maintained at formation pressure, or

- the sample may be transferred under pressure into alternate pressure containers for storage and transport.

The advantages of this discrete sampling method can be summarized as follows:

1) The sample is drawn directly from formation fluids outside the measurement port. Therefore, there is no need for pumping a number of well volumes prior to collecting each sample. Because there is no pumping prior to sampling, the sample is obtained with minimal distortion of the natural groundwater flow regime, the storage and disposal of large volumes of hazardous purge fluids is eliminated, and operator exposure to hazardous fluids is reduced.

2) The lack of pumping means samples can be obtained quickly, even in relatively low permeability environments.

3) The sample travels a short distance into the sample container, typically from 1 to 2 ft [30 to 60 cm], regardless of depth.

4) The risk and cost of storing and disposing of hazardous purge fluids is virtually eliminated.

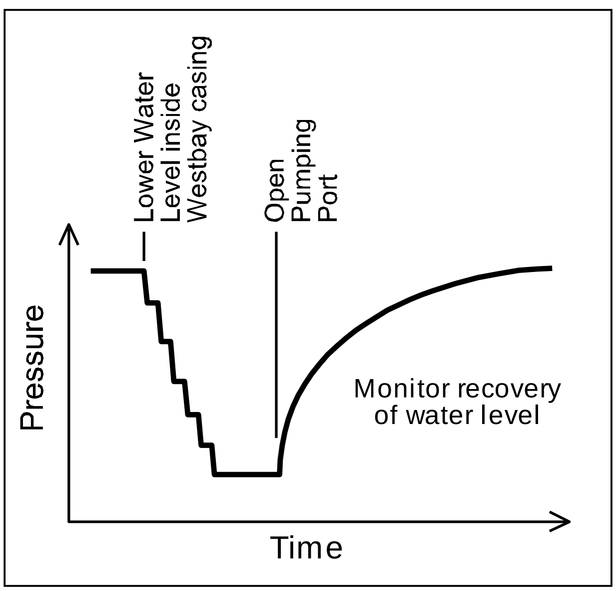
Hydraulic Conductivity Testing

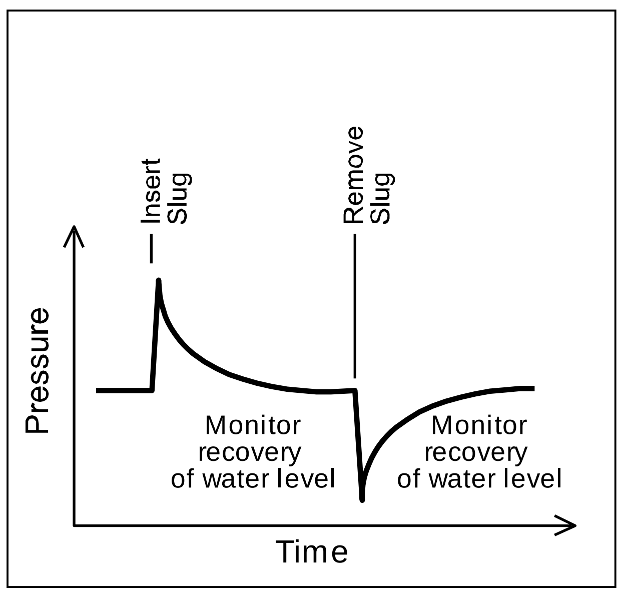
Using the Westbay System a variety of different test methods can be employed to evaluate the hydraulic conductivity of formation materials. These include variable head, constant head and pressure-pulse tests.

Variable head tests are the single well test method most commonly used with the Westbay System. Using these types of tests in the Westbay System, hydraulic conductivities between 10^{-2} and 10^{-8} cm/sec can be determined.

For variable head tests the pumping ports are used to provide the hydraulic connection between the interior of the Westbay casing and the test zone. In cases where monitoring zones are to be purged, it is convenient to carry out hydraulic conductivity testing just prior to or following purging. With all the port valves closed, the head (fluid level) inside the Westbay casing can be adjusted, then the selected pumping port can be opened in a controlled manner (pumping port operation is described in the discussion of purging). This allows accurate measurement of both the initial head change and the time at which the head change is applied (t_0). The pumping port valve is opened rapidly (in less than one second), which satisfies the theoretical requirement that an instantaneous head change be applied to the tested zone. The use of a transducer (such as the Westbay probe or a Diver*) inside the Westbay casing eases recording of the recovery of the water level during the test.

For rising head tests the water level inside the Westbay casing is bailed or pumped down to a pre-determined level below the static water level in the test zone. For falling head tests the water level is raised to a level above the static water level in the zone to be tested. Measurement equipment is set in place and the pumping port valve is opened. Recovery of the water level in the Westbay casing is measured and recorded vs. time. A pressure transducer is commonly used to record the water level changes. Figure 11 shows a typical record of water levels during a rising head hydraulic conductivity test.





Slug tests are carried out by opening the pumping port coupling at the zone to be tested and allowing the water level in the Westbay casing to equilibrate to the static water level for that

Figure 11. Typical data record from a rising-head test.

Figure 12. Typical data record from a slug test.

zone with measurement equipment in place. The initial head change is then applied by rapidly lowering a displacement slug (a length of solid rod or sealed pipe) into the water. The recovery of the water level is measured and recorded vs. time. The slug test can be repeated and recorded again when the slug is removed from the water. Figure 12 shows a typical record of water levels during a slug test of hydraulic conductivity.

Data from variable head hydraulic conductivity tests may be analyzed using any preferred calculation method. The most commonly used methods are those of Hvorslev (1951), Cooper et al. (1967) and Bouwer and Rice (1976). Selection of these or any other analytical method should be based upon an assessment of how well the test conditions comply with the simplifying assumptions inherent in the analytical method. Software packages such as AquiferTest* provide a selection of analytical methods that can be applied.

In very low permeability environments (hydraulic conductivity less than 10^{-7} or 10^{-8} cm/sec) the formation fluid pressure can be changed with very little fluid movement. As a result, tests can be carried out through the measurement port valve rather than the pumping port valve. Using a sampler probe with a transducer the zone to be tested may be exposed to the fluid pressure inside the Westbay casing for a period of time (see Fig. 7 and discussion of measuring fluid pressure in low-k environments). The zone may then be shut-in and the recovery of fluid pressure over time measured and recorded. Figure 8 shows a data record from such a test.

Field Quality Control

There are two distinctive parts to any quality assurance program. The first involves manufacturing and testing procedures which avoid the production or installation of equipment that may result in the collection of erroneous data. The second involves field operating procedures which will ensure that erroneous data are not generated as a result of the failure of any component to function as intended. Although the first part is necessary to allow the installation of useful monitoring wells, the second must also be rigorously applied to identify sources of erroneous and misleading results.

The Westbay System has many unique features for field quality control which clearly separate it from other types of groundwater monitoring instrumentation. These features are the result of designing components in response to the stringent requirements of users in the fields of nuclear and hazardous waste management.

Quality control tests are carried out at various points during the field use of the Westbay System and tend to be grouped into three periods: during installation, following installation, and during routine monitoring.

During Installation

During installation of the Westbay System the following operations form part of the quality control procedures:

Drill core or cuttings and borehole geophysical logs are carefully checked to see that monitoring zones and annular seals are placed at the optimum positions. In cased wells, the well casing is inspected to verify that the interior surfaces are suitable for establishing good quality packer seals and backfill is placed under carefully controlled conditions with frequent measurements of material depths.

Westbay casing components are carefully inspected to see that critical surfaces are undamaged, sealing o-rings are clean and in place, and components are correctly oriented. Serial numbers are recorded along with component position in the installation. These operations link the field quality control to production test records.

As each section of Westbay casing is attached, the connection is pressurized with water and observed for any signs of leakage. Test results are recorded on the installation log.

Before inflating packers, a pre-inflation profile of pressure measurements is made through the measurement ports. This serves to verify the proper operation of components before being fixed in the well.

During inflation of each Westbay packer, incremental volumes and pressures are recorded and plotted. These data allow an evaluation of borehole conditions and provide the first indication of the quality of the annular seal obtained.

Following Installation

Immediately following installation further checks are carried out to verify the operation of the system. These include the initial post-inflation pressure profile which provides the first data on the vertical head distribution. Observed head differences across exterior casing seals directly indicate the seal effectiveness. Where such head differences are not observed, the annular seals can be artificially stressed by opening a pumping port in one monitoring zone and withdrawing or adding a slug of water from inside the casing while using a pressure probe or sampler probe to observe the pressure response in the monitoring zone on the other side of the seal. In cased wells and wells in low permeability environments, stresses can be applied through measurement ports in order to evaluate seal integrity.

Additional measurement ports are routinely installed between monitoring zones, further enhancing the ability to carry out thorough quality control tests.

Fluid can be added to packers at any time following installation and the pressure at which further fluid injection occurs can be compared with the injection pressures recorded during the initial inflation.

During Routine Monitoring

A number of quality control checks are built into the routine monitoring procedures.

When measuring fluid pressures, the pressures measured inside the Westbay casing at each measurement port are recorded immediately before and after the measurement made through the port. These inside casing values serve a number of purposes: 1) comparison of the two values confirms that the transducer was operating the same way before and after the reading, 2) comparison of the inside values from one set of measurements to the next confirms transducer stability over the intervening time period (assuming the water level inside the casing is the same), and 3) if the head of fluid inside the Westbay casing is known, an in-situ calibration check of head of water versus transducer output is obtained. Any unacceptable changes which show up during monitoring can be checked and corrected through laboratory calibration of the instrument.

Water sampling procedures with the Westbay System improve quality control because: 1) the short flow path between the formation and the container greatly reduces the surface area contacted by the sample, 2) the contacts between the water sample and the atmosphere are eliminated, 3) observing and recording the water level inside the Westbay casing during sampling confirms that the sample obtained is from outside the casing, and 4) sampling without purging reduces the disturbance of the natural system, minimizing unnatural changes in chemistry. Sampling methods can be varied to compare the effects of atmospheric contact versus no atmospheric contact and maintaining the sample under pressure versus allowing depressurization of the sample.

During water sampling, sample blanks and spikes may be collected using identical procedures for sampling, preservation, handling and shipping. Travel blanks and spikes may also be collected using identical procedures for handling, preservation and shipping. The chemical analyses of samples obtained using the Westbay System may be compared with those of samples collected from the same zone by alternate means.

Finally, the pumping port may be reopened should further purging appear to be desirable.

For both fluid pressure and water quality data, the Westbay System can provide corroborative data. That is, a high density of data can be obtained in a single installation so that significant changes in piezometric pressure and/or water quality can appear as transitions along a depth profile. Thus, neighboring values will corroborate one another rather than indicating abrupt changes which would cause one to question anomalous values.

Serviceability

In the event that quality control testing should reveal a component which is not operating properly, various steps can be taken to remedy the problem including, in certain cases, removing the Westbay casing string, replacing faulty components and reinstalling the string.

Summary

The modular nature of the Westbay System permits a large number of monitoring zones to be accessed through valves placed along a single closed tube or casing installed in a single borehole. Such a monitoring system can provide a detailed view of the variation of piezometric pressure, hydraulic conductivity, and water quality with depth. The valved couplings permit purging of the well following installation and allow all standard hydrogeologic tests to be carried out in each zone. Routine sampling is carried out without repeated purging, eliminating the need to store and dispose of large volumes of purge fluid and reducing operator exposure to hazardous fluids. The valves also permit an evaluation of the condition of exterior casing seals at any time after installation. Casing packers allow multiple seals to be established easily and quickly, providing the required hydraulic isolation of each monitoring zone. The modular design of the downhole components means the number and location of monitoring zones and seals can be modified on the basis of the best information available in the field at the time of installation. The exact depth of monitoring zones need not be known when equipment is purchased.

Figure 13 provides a schematic summary of the most common operations carried out in Westbay System monitoring wells. These include:

a) Purging and testing through open pumping ports;
b) Sampling and testing through measurement ports;
c) Pressure profiling using a single probe;
d) Automated monitoring using a string of pressure probes and a data logger; and
e) Vertical interference testing using a pressure probe and a sampler probe.

Other operations can also be carried out, such as cross-hole testing, vertical interference testing using strings of pressure probes, in-situ chemical analysis, tracer testing, etc.

Figure 14 provides a representation of the many types of data than can be collected from a single Westbay monitoring well. Among groundwater monitoring technologies, the ability to complete any number of monitoring zones in a single borehole and to carry out the variety of operations that permit the collection of data types represented here, all while maintaining high standards of quality assurance, is unique to the Westbay System.

Field quality control procedures have been established which permit the quality of a well installation and the proper operation of testing and sampling procedures and equipment to be routinely verified. Thus, groundwater data and the additional data required to define the quality of the field data can be routinely collected. Furthermore, when a high density of groundwater monitoring zones are installed by using multilevel monitoring wells, the redundant monitoring points can provide important corroborative field data to an extent which is not available with single level monitoring wells. The result is a monitoring system which provides data with a degree of defensibility unattainable with any other monitoring method, single or multilevel.

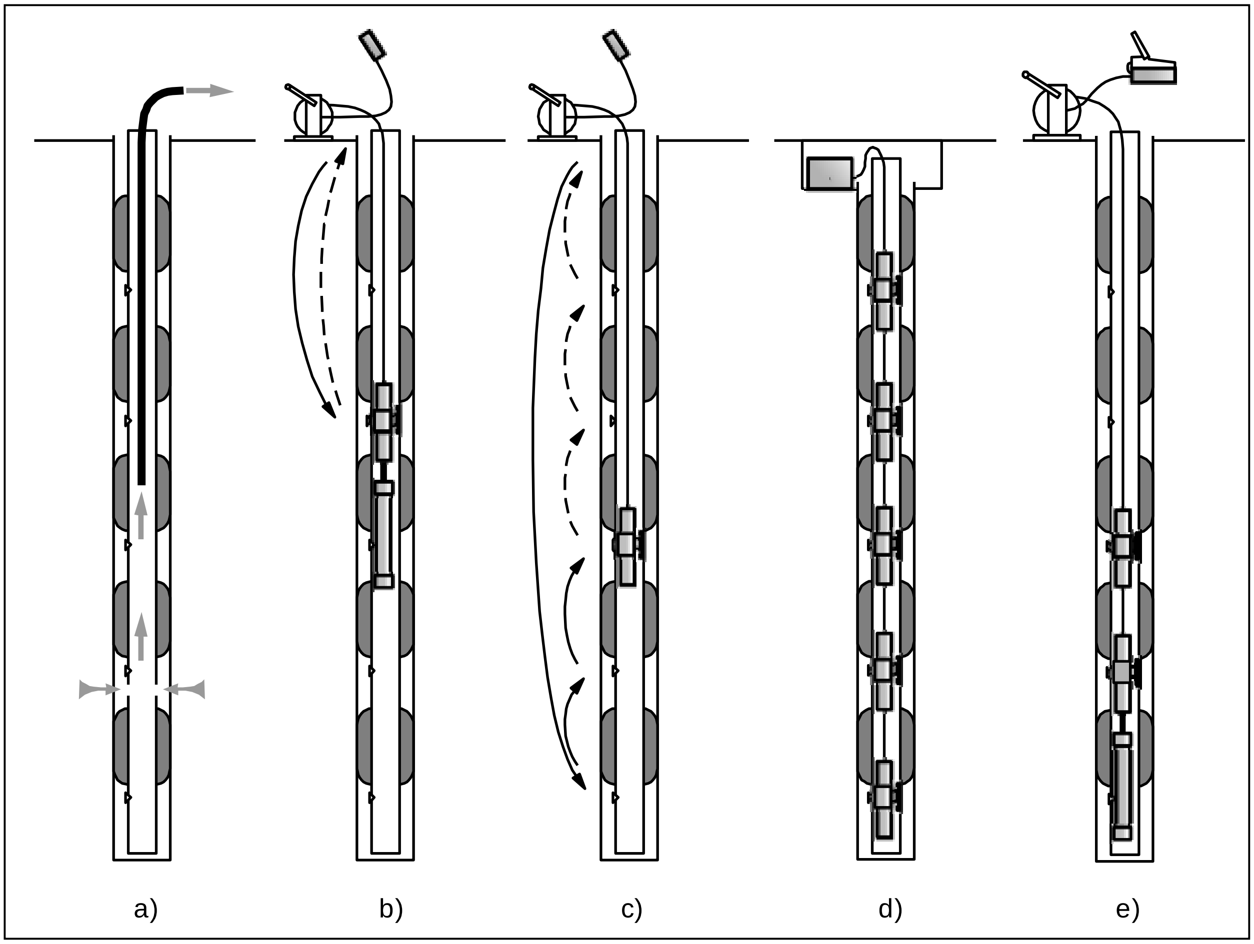


Figure 13. Schematic illustration of common operations with the Westbay System.

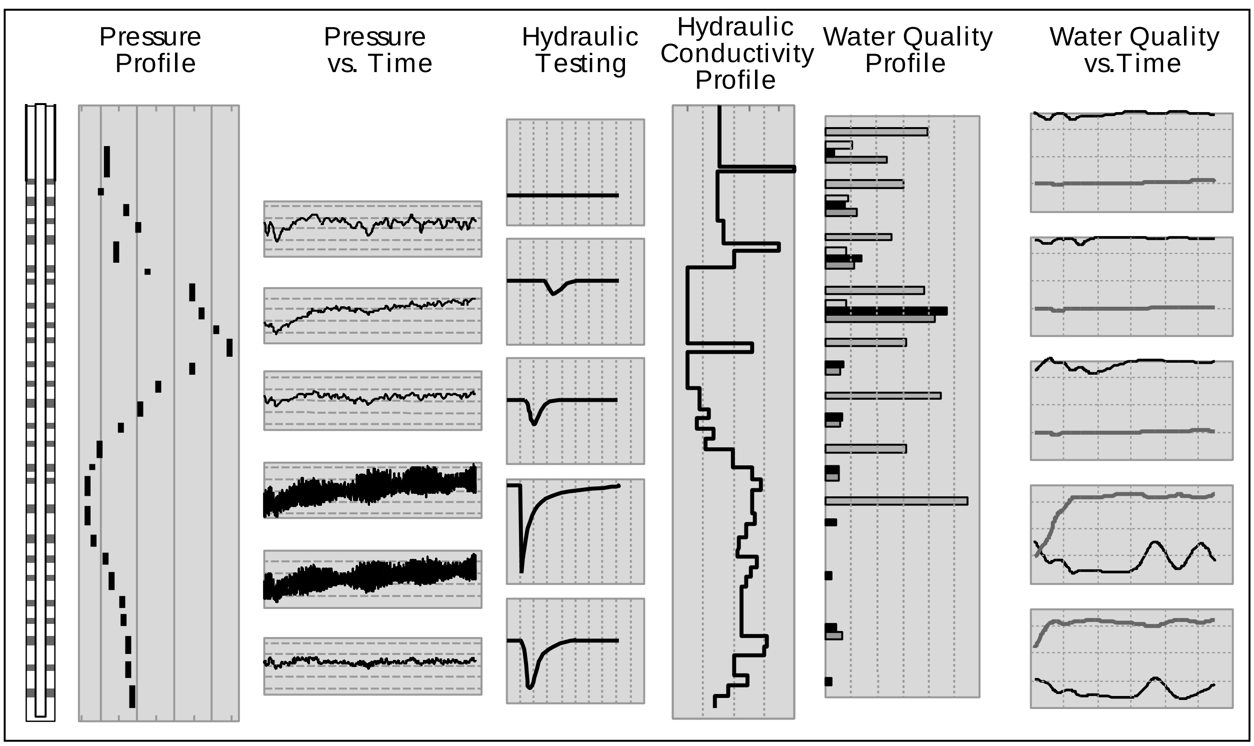


Figure 14. Schematic illustration of the types of data that can be collected with one Westbay well.

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* Mark of Nova Metrix Ground Monitoring (Canada) Limited, Westbay Division

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