SPE-177007-MS

The anisotropy and inhomogeneity of coal permeability and interconnection of adjacent seams

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This paper was prepared for presentation at the SPE Asia Pacific Unconventional Resources Conference and Exhibition held in Brisbane, Australia, 9–11 November 2015.

Abstract

The purpose of this work was to develop a method by which the anisotropy and inhomogeneity of permeability of coal seams and other reservoirs could be rapidly determined at exploration stage. As inhomogeneity can only be determined by multiple tests and anisotropy can only be found by some form of interference test, the intention was to develop an efficient combination of the two.

This was achieved by using drill stem testing (DST) multiple seams in a single borehole followed by the installation of pressure transducers in the coal seams. Another hole was then drilled and DST tested and the transient response in the transducers measured. This was again followed by transducer installation and the drilling of another hole which was then DST tested. Also tested was the interconnection of seams across thin mudstones and a tuff band. The transducer installation was accomplished using cemented in transducers with the cement being displaced in the vicinity of the transducer to establish connectivity with the formation.

The results of the work showed that in the test site inhomogeneity dominated over anisotropy and that the interburden between the seams was highly impermeable. Reliable permeability measurements were achieved by analysing transients of less than 6 kPa (0.86 psi) from a pre and main flow DST.

This process was quick to implement and therefore of low cost. The number of measurements achieved was higher than would have come from a conventional interference test. The multiple boreholes in which flow took place avoided the problem of a conventional interference test, with a single producing hole, which may have been located in a geologically unusual setting.

Anisotropy or Inhomogeneity

The question as to whether a formation exhibits anisotropy, inhomogeneity, or both, is important in determining a production strategy. Here anisotropy means directional permeability, and inhomogeneity means variability of permeability with location. In addition inhomogeneity of anisotropy means that the directional permeability varies, though not the mean value.

In the case of coal seams with significant cleating the directional permeability has been found in some cases to be so dominated by the major permeability as to make the measurement of the minor permeability virtually impossible. The Gemini seam in Blackwater, Central Queensland and the Bowen Seam at Collinsville in North Queensland are examples of this behaviour. In-seam drilling in the direction of the principal cleat would yield virtually no flow except where the hole intersected major joints or faults. However if drilling across the cleat was conducted significant and even flows into the borehole resulted (Gray, 1983, 1987).

Most exploration for coal seam gas is conducted by wireline coring from surface and drill stem testing is the most reliable and simple means to test for the permeability of these seams. However such tests only yield a mean value of permeability with no directional information. The testing does however provide a good indication of the variation in permeability over an area. This may show regional trends or simple inhomogeneity. Sometimes there is a significant variation in the permeability determined from such tests despite there being only a few hundred metres between holes.

If a normal interference test is conducted with a production or an injection hole surrounded by observation holes fitted with pressure transducers, then there is a difficulty in separating inhomogeneity from anisotropy. The minimum number of observation points to solve for conditions of anisotropy is three. There is a single unique solution to the major and minor permeability and their directions from these three wells. The only way to determine inhomogeneity in permeability is to compare the permeability derived from the central well with the mean of that from the interference wells. This may be augmented by a comparison of the compressibility – porosity products from analysis of pressure change in each of the interference wells. If more observation wells are used then a better idea of the inhomogeneity may be gained. The measurement may however be dominated by the nature of the geology surrounding the production hole.

The alternative to an interference test is frequently a production trial with multiple production wells. This can take the form of a five spot vertical well production trial. In this case the central well can be mathematically considered to behave similarly to an array of similar wells with the outer wells behaving as cut offs to incoming flow from the reservoir. Such a production trial is an expensive operation and still does not reliably answer questions as to the importance of anisotropy and inhomogeneity. The lack of pressure sensing makes the analysis of reservoir behaviour difficult, especially where these are coal seams as there is insufficient information to determine unique reservoir parameters from history matching of production well behaviour based on in well pressure and flow rates.

The analogue of the five spot production trial for horizontal completions requires three wells in the two directions of principal permeability. This is a major cost which few companies are prepared to engage in. The usual mode is to guess the direction of principal permeability and drill a one or two hole trail perpendicular to it. The full analysis of such trials also requires reservoir pressure measurement.

Formation Pressure Sensing

The need has therefore been established to measure pressure in the coal seam or other formation that needs to be monitored. This is more complex than it may first appear and there are many traps in achieving a good outcome. The keys to good pressure sensing are certainty of what is being measured and reliability. Certainty can only be achieved if the system can be tested. Reliability comes from good equipment and good installation practice.

The options to install pressure sensors include removable systems and those that are permanently installed. The removable systems are usually packer based and used for installation inside casing that has been perforated to connect it with the formation. While it may be considered that the removable systems are superior because they can be serviced, the cost of doing so is considerable as it requires removing the packer and transducer system from a live well that needs to be kept under control. The cost of this may easily exceed that of the initial installation.

The permanent transducer installations usually involve cementing transducers into the well. As such they rely on communication between the pressure sensing diaphragm of the pressure transducer and the formation to be monitored. To establish this communication the cement used must have some permeability and yet not enough permeability to enable pressure connection between the various formations intersected by the well. These are conflicting requirements.

The process of cementing transducers into a well is further complicated by the filtration of the cement grout mixture into the formation under hydrostatic pressure within the well. This leaves a very dense impermeable mixture next to the formation to be monitored. The consequence of this is that the transducer response may be slowed by some months (Neels and Gray, 2014).

The solution to these problems was the development of cement grouted installations with the displacement of cement from around the filter of the transducer and the borehole wall. It enables the use of low permeability cement grouts that avoid problems with intra-well connection between transducers and permits the transducers to operate in an installation that is independent from the cement grout-formation interaction. It also provides a means by which intra-well connection can be tested and where communication with the formation to be monitored may also be tested.

This type of installation involves the placement of permanent pressure transducers in a borehole. In this application, a cement grout pipe is fitted with pressure transducers, cables and cement displacement lines and then lowered into the borehole. By preference, this is undertaken inside a casing or wireline drill pipe (in this case Boart Longyear HQ pipe of 89 mm OD and 78 mm ID). This drill pipe is then withdrawn over the grout pipe assembly and the assembly is picked up from what will be a helically buckled form in the hole and hung from the hole collar so as to locate the sensors at the pre-determined positions. This is the situation shown schematically in Figure 1. Here a single transducer is shown hanging in the well with a cable attached. It is connected to a fitting to which a filter is attached and so is a pressure relief valve. The pressure relief valve is designed to support the water column above it in the injection tube. This injection tube is either nylon or stainless steel depending on the depth and application.

- Figure 1A shows the operation of pumping water through the injection tubing to clear the filter.
- Figure 1B shows the hole being cement grouted.
- Figure 1C shows the filter being cleaned with a small quantity of water.
- Figure 1D shows the cement grout being displaced by water injection when it has reached a plastic state.

The actual installation process involves installing transducers on tubing containing pockets to protect them. This tubing is of steel, or where mining may take place, it has been replaced by fibreglass. The transducers are connected by cable to the surface. Their diaphragms have been connected to a common chamber with a filter and a pressure relief valve that is in turn connected to the surface by the injection tubing.

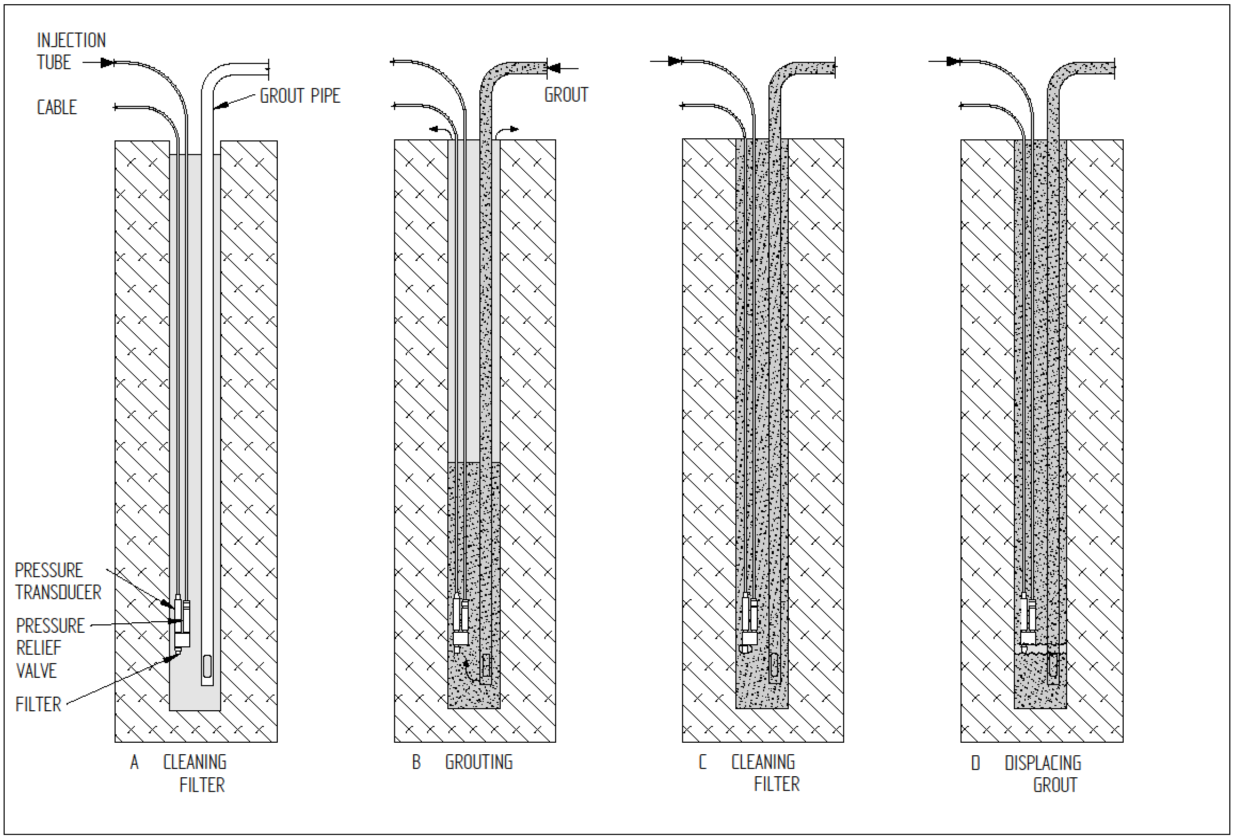

Figure 1. The installation sequence of a pressure transducer by cement displacement.

In the case described in this paper, five transducers were installed in the hole as closely as two metres apart. Injection testing through the capillary tubing following the setting of the cement grout, showed no interconnection within the borehole. Decay of pressure took place indicating connection to the coal seams being monitored. Figure 2 shows the results of pressurisation and pressure decay during this test period. The large pressure spikes and their subsequent decay are caused by pumping into each filter zone. The small responses in adjacent sensors are due to the expansion of the nylon injection tubing in the adjacent filter zone.

The transducers used were vibrating wire devices that are generally used in civil and mining applications. They are extremely stable over very long periods and produce a frequency output that can be read to 1/1000 th of a Hertz in a signal lying between 2000 and 3000 Hz bandwidth. The theoretical sensitivity is therefore 1 in 10^6. Practically the sensitivity achieved was within a bandwidth of 0.04 kPa (0.006psi) in a 10000 kPa transducer, corresponding to 1 in 250000. The accuracy of these devices is really dependent on the quality of calibration. With careful calibration this can reasonably be within 0.05 % of full scale. As they are a fraction of the cost of quartz sensors and provide a digital (frequency) signal they are a good, cost effective transducer for reservoir monitoring.

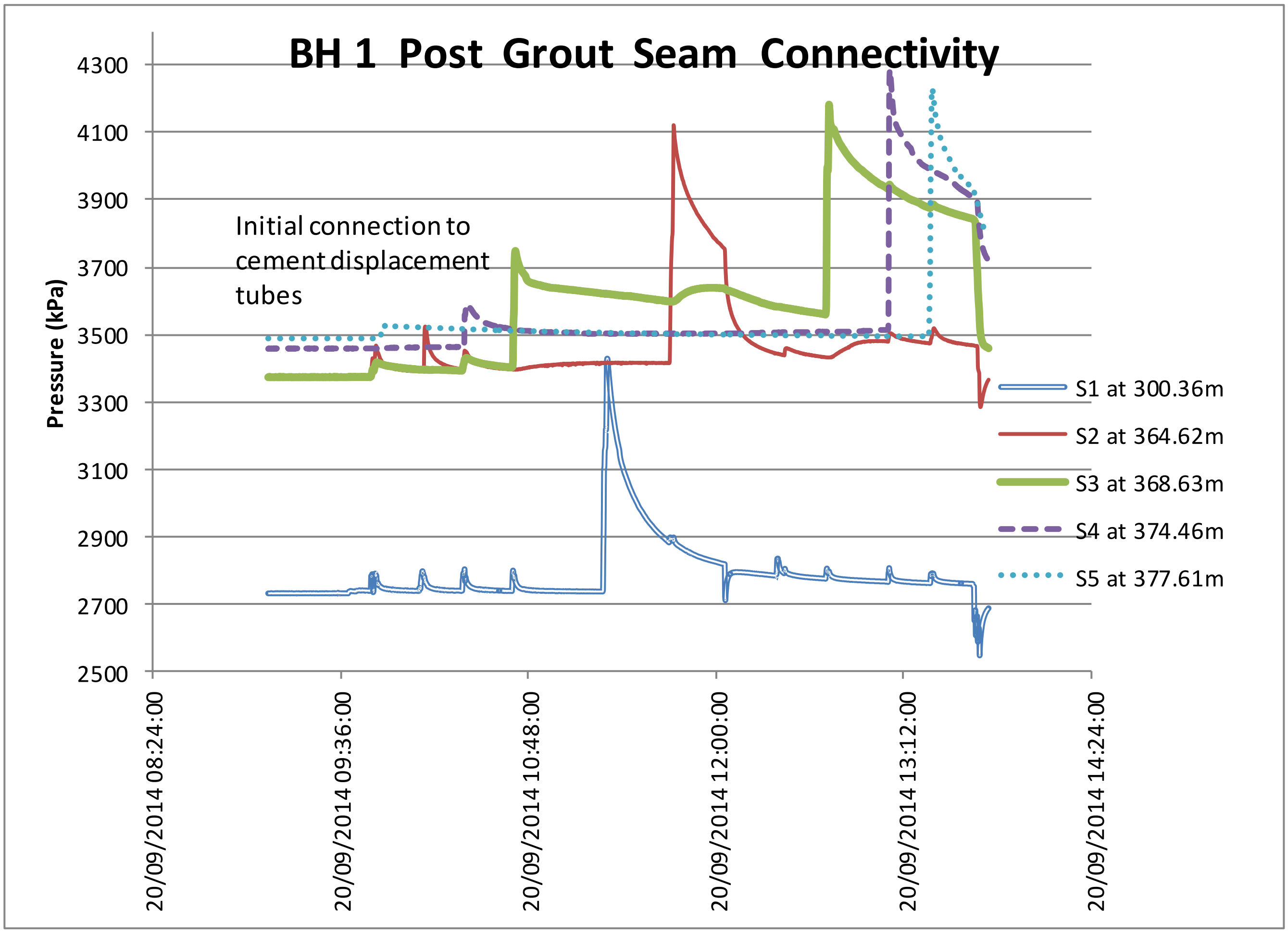

Figure 2. This shows injection into each seam level and the associated pressure spike and decay.

This case was for an installation between 290 to 380 m depth. Others have been completed without complications to 600 m and no major problems are forseen in using the system to greater depths. In deeper installations the nylon can be replaced by stainless steel capillary tubing. The system is subject to patent applications.

Geological Environment

The case study involved a coal seam bearing sub basin in Queensland. A density log of this is shown in Figure 3 for borehole 1 of the group of holes drilled. It shows an upper coal seam (1) at 292 to 297 m and then a group of seams from 356 to 378 m depth. The latter group comprises a main seam (2) from 356 m to 361 m which is separated from seam 3 by a tuff band and then a sequence of interbedded seams and shales. In the latter seams (4) and (5) are identified. Pressure transducers were installed in seams 1 to 5 by the method described above. Their locations are marked in Figure 3.

Examination of the acoustic scan records from the boreholes show borehole breakout in the seams that changes direction quite abruptly. This and direct stress measurements indicate a complex stress pattern that changes with location in all dimensions and is mirrored in the complex fault patterns in the area.

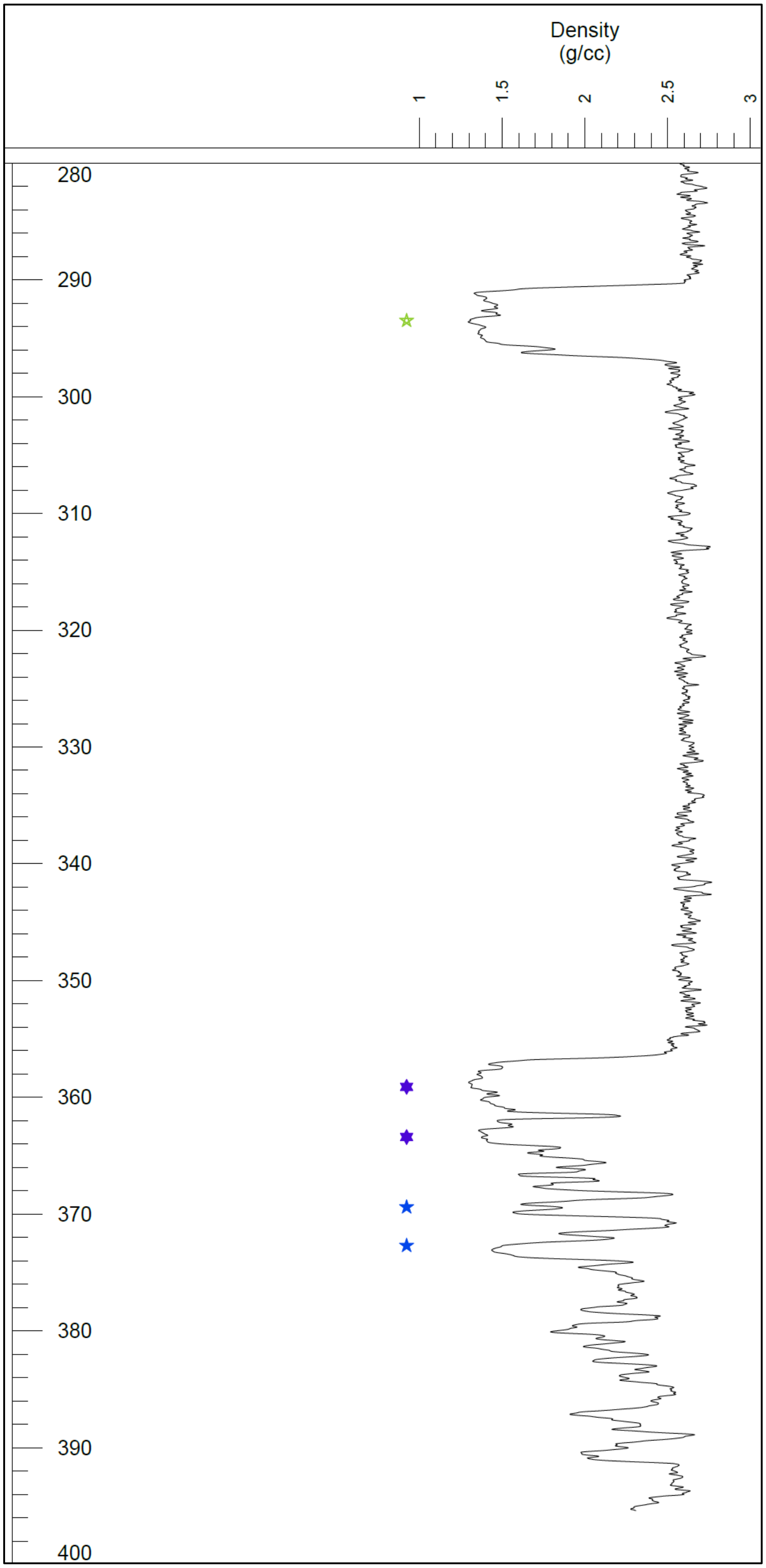

Figure 3. Density log of the coal-shale sequence with pressure transducer locations indicated by stars.

Formation Testing

The purpose of the formation testing was to evaluate the degree of anisotropy of the coal and to test for interconnection between the various seams. Two sites approximately 700 m apart were tested. In each case an initial hole was drilled with wireline coring from above the coal seams to below the seams of interest. The drilling coring process was interrupted to obtain stress measurements in the rock by overcoring using Sigra's IST tool. This yielded results that showed a consistent direction of principal stress which approximately aligned with the major cleating in the area. At the completion of the first hole a series of drill stem tests were conducted using Sigra's DST tool that operates on wireline and is deployed through the core rod string. Permeabilities were determined using conventional drill stem test analysis of derivative and Horner plots. The permeabilities varied from 0.02 to 12.5 md, dependent on the seam. Seam 1 showed the highest permeability while seam 4 showed the lowest. The DST tool had a pressure transducer memory gauge installed below the lower packer to detect any effect on pressure below the test zone. None was observed.

This first hole was then fitted with pressure transducers and cement grouted in the method described above. An offset well was then drilled for the purpose of conducting another set of drill stem tests. The offset well was oriented along the direction of the expected major permeability as deduced from stress measurements and the cleating orientation determined from acoustic scans of the borehole. The spacing of this offset well from the first well was limited by the seam of lowest permeability. This meant that spacings of 25 m were planned. This was approximately achieved though borehole drift from vertical meant that this was not consistent and the actual relative location of each of the holes in each seam had to be determined from borehole survey logs.

The second hole was then tested by the DST process. It yielded both a permeability value for the hole being tested and a pressure variation in the hole being pressure monitored. The analysis of the pressure variation in the transducers installed in the first hole was by fitting the radial diffusivity equation (1) to the pressure trace.

$$p(i) - p\,(r,t) = \frac{q\mu}{4\pi kh}\int_{\infty}^{x}\frac{e^{-s}}{s}\,ds \tag{1}$$

$$x = \emptyset\frac{\mu c r^2}{4kt} \tag{2}$$

Where
p(i) is the initial pressure
p (r,t) is the pressure at radius r and time t after the start of flow
q is the flow rate
μ is the viscosity
h is the seam thickness
r is the radius from the producing well to the pressure measurement
c is the total compressibility
k is the permeability
∅ is the porosity
t is the time from the start of flow

The flow and non-flow periods were simulated by a process of superposition of positive and negative flows. The overall solution was by separating the effects of the pulse(s) from the background pressure trend and then solving the radial diffusivity equation for the only unknowns; the total compressibility-porosity product (*c.*∅) and the permeability (*k*). The solution was obtained by a least squares solution, using a Newton Raphson process to fit the radial diffusivity equation to the experimental data set.

An example of a DST is shown in Figure 4. This shows packer pressure, test zone pressure and in pipe pressure. The latter is used to determine fluid inflow. There was no measureable gas inflow during the test process.

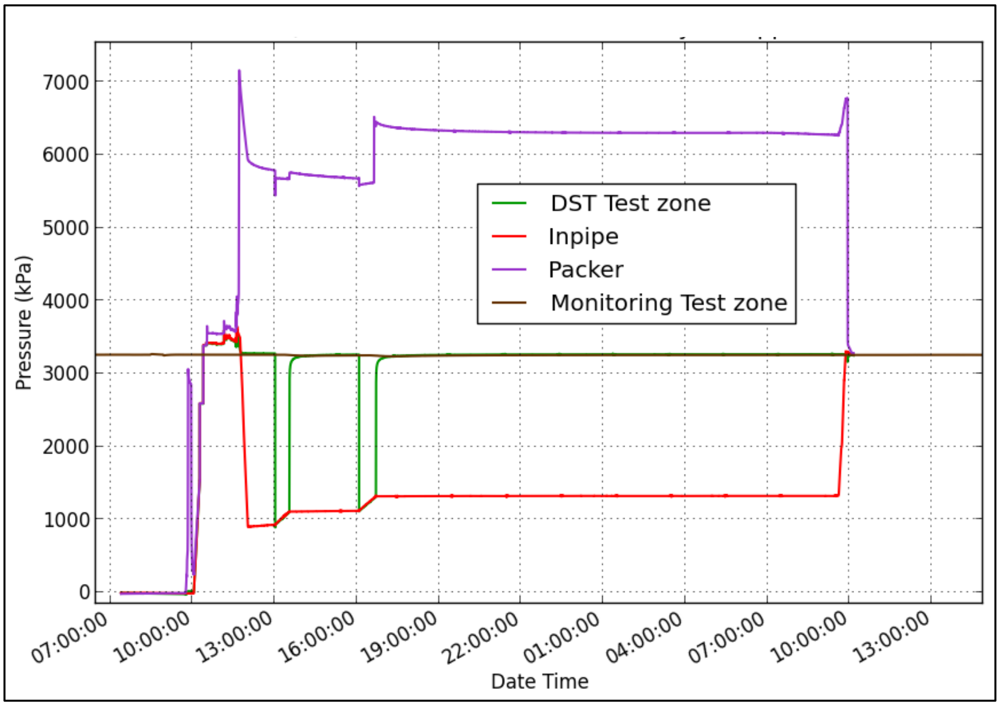

Figure 4. DST pressure traces for test in seam 2 of hole 2.

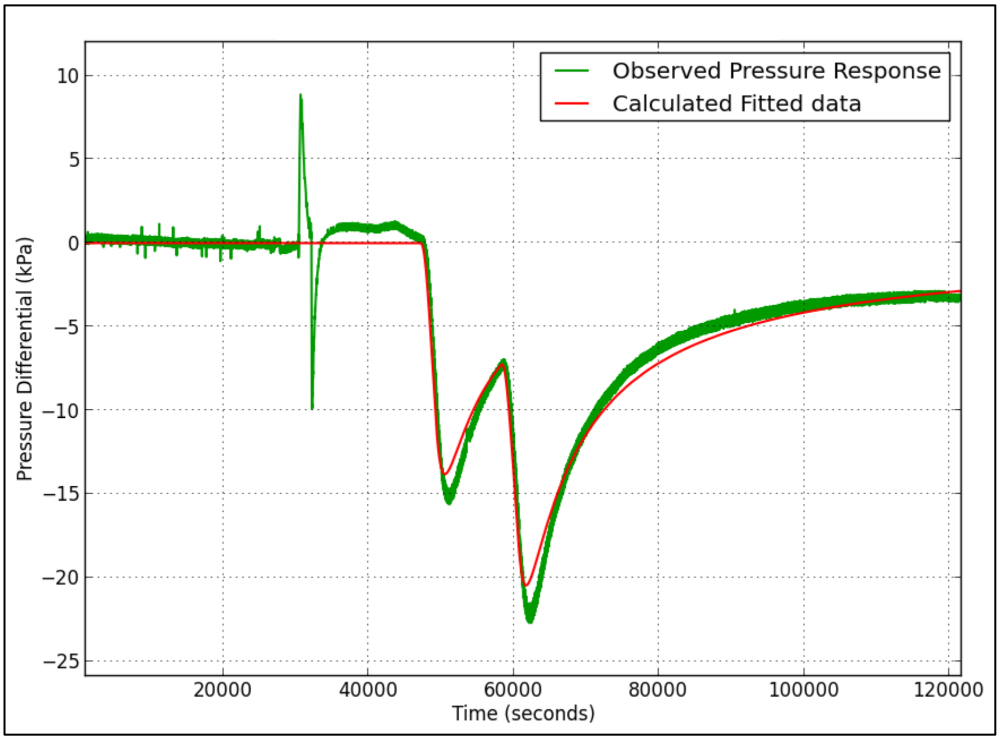

Figure 5. Pressure traces from transducers in seam 1, hole 1 with matched trace.

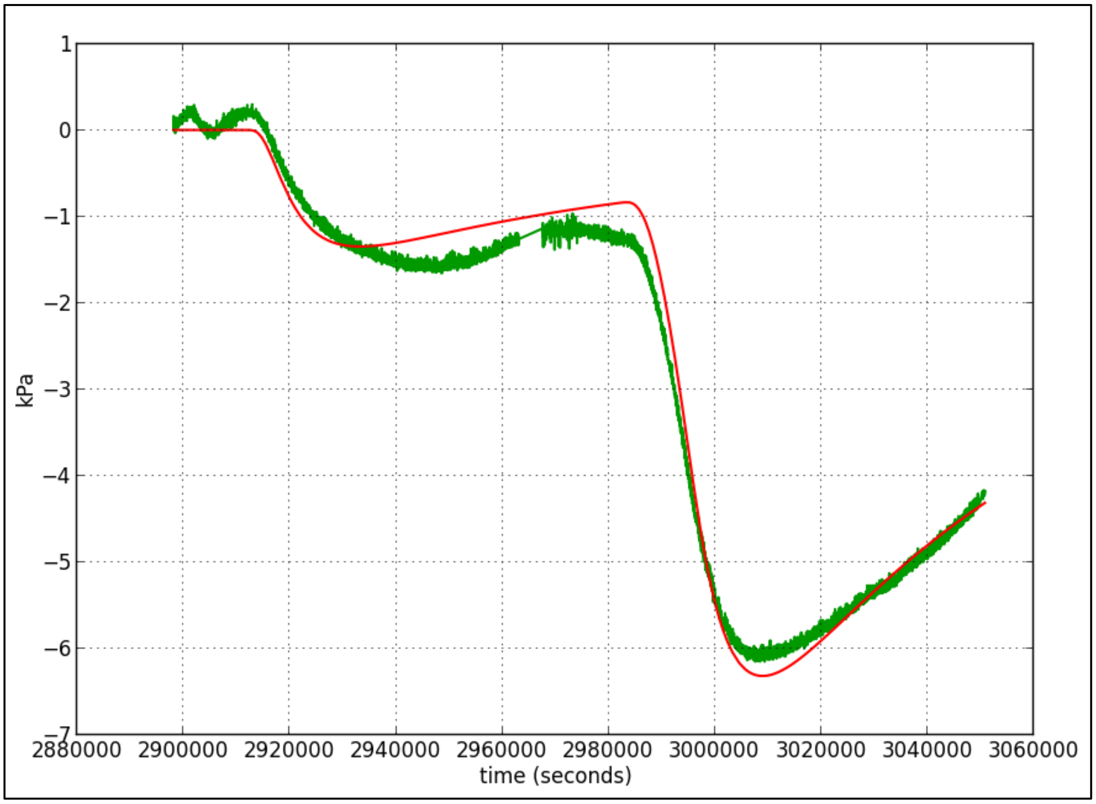

Figure 6. Pressure traces from transducers in seam 5, hole 1 with matched trace.

Figure 5 shows the pressure trace recorded in the transducer in hole 1 monitoring the DST along with the fitted pressure match, which is of reasonable quality. Figure 6 shows the trace from the transducer in the lower permeability seam 5 along with the matched trace, the fit of which is also reasonably good.

A two hole trial such as that described can yield two values of mean permeability from each DST. It can also provide an inter hole value of permeability and the total compressibility-porosity product. If the mean values are the same it is theoretically possible to determine the value of the directional permeability that is orthogonal to the line between the holes by rearranging equation 3.

$$k_{mean} = \sqrt{k_x k_y} \tag{3}$$

Where k_{mean} is the mean permeability
k_x is the permeability in the x direction
k_y is the permeability in the y direction

If the original direction between holes lies on a principal direction of permeability then the orthogonal permeability is also a principal value. Another borehole is theoretically required to determine the directions of principal permeability in a uniformly (homogeneous) anisotropic reservoir.

Test Results

The test results are presented in Tables 1, 2 and 3.

		Hole 1	Inter Hole	Hole 2	Max	Mean DST	Min	Perm Ratio	Direction
Seam 1	Perm (md)	2.04	0.573	1.09	4.27	1.565	0.57	7.46	NW
	$c.\emptyset\times10^{12}$ (Pa^{-1})		42						
Seam 2	Perm (md)	12.6	13	12.4	13	12.5	12	1.08	NONE
	$c.\emptyset\times10^{12}$ (Pa^{-1})		244						
Seam 3	Perm (md)	9.6	13.1	8.51	13.1	9.055	6.26	2.09	NE
	$c.\emptyset\times10^{12}$ (Pa^{-1})		423						
Seam 4	Perm (md)	0.194	N/A	0.0987		0.146		N/A	N/A
	$c.\emptyset\times10^{12}$ (Pa^{-1})		N/A						
Seam 5	Perm (md)	0.395	0.752	0.386	0.75	0.391	0.2	3.71	NE
	$c.\emptyset\times10^{12}$ (Pa^{-1})		138						

Table 1. Holes 1 and 2. Permeabilites from DSTs and from the analysis of the interference trace. Porosity-compressibilty products from the analysis of the interference trace. Maximum or minimum permeability estimates from equation 3.

	Hole 3	Inter-Hole	Hole 4	Inter-Hole	Hole 5	Mean DST	Mean Pulse	Perm Ratio	Direction
Perm (md)	2.55	1.07	0.921	0.858	0.579	1.35	0.964	1.247	NW
$c.\emptyset\times10^{12}$ (Pa^{-1})		1010		282					

Table 2. Holes 3, 4 and 5. Seam 1.

		Hole 3	Inter Hole	Hole 4	Max	Mean DST	Min	Perm Ratio	Direction
Seam 2	Perm (md)	1.87	1.67	2.94	3.463	2.405	1.67	2.07	NE
	$c.\emptyset\times10^{12}$ (Pa^{-1})		1699						
Seam 3	Perm (md)	0.296	10.57	1.01	10.57	0.653	0.04	262.01	NW
	$c.\emptyset\times10^{12}$ (Pa^{-1})		40218						
Seam 4	Perm (md)	0.126	N/A	0.0224		0.074		N/A	N/A
	$c.\emptyset\times10^{12}$ (Pa^{-1})		N/A						
Seam 5	Perm (md)	0.135	1.47	0.0607	1.47	0.098	0.007	225.69	NW
	$c.\emptyset\times10^{12}$ (Pa^{-1})		9258						

Table 3. Holes 3 and 4. Seams 2, 3, 4 and 5.

In the case of holes 1 and 2 all the tests were of high quality and permitted matches of the quality shown in Figures 5 and 6. The seam permeabilities in Table 1 showed the following trends:

In Seam 1 the permeability varied by 2:1 from the two DST's and the interference value was nearly half the lower DST value. Also the direction of major permeability was orthogonal to that expected. The calculated maximum permeability value is 4.27 md and the permeability ratio is therefore 7.5:1

In Seam 2 the permeability measured was very even.

In Seam 3 the permeability was variable and in the direction expected with an estimated permeability ratio of 2:1.

In Seam 4 the permeability was low and no interference was detected. The DST derived permeabilities are different by a 2:1 ratio.

In Seam 5 the DST derived permeabilities were very similar and an inter hole permeability that is double this. The derived permeability ratio is 3.7:1 in the direction expected.

Table 2 shows the case of holes 3, 4 and 5 for Seam 1 in the second test location. All testing was of high quality and shows the following:

Hole 3 was drilled and tested. It then had a transducer string installed and hole 4 was drilled and tested. This was followed with the drilling and testing of hole 5 which was drilled orthogonally to the line of holes 3 to 4 but without the sealing of hole 4. The DST derived permeability values differed by a ratio of 4.4:1. The interference pulse derived permeabilities were however similar.

Table 3 shows the results of drilling and testing hole 3 for Seams 2, 3, 4 and 5. This hole then had transducers installed and was followed by testing in hole 4. It shows the following:

Seam 2 in this location had a permeability that was quite different from that found in holes 1 and 2. There was also a significant difference between the DST derived permeabilities and the permeability derived from the good quality interference trace. While a permeability ratio of 2.1 may be calculated based on the mean DST derived permeability combined with the interference trace it is just as likely that the permeability increased from hole 3 to hole 4. The apparent directional permeability was in the expected direction.

Seam 3 showed a very different picture with DST derived permeabilities of 0.3 and 1.0 md but with an inter hole permeability from the rather poor match of 10.6 md. This high permeability was not in the expected direction.

Seam 4 showed low and very low DST derived permeabilities and no analysable pressure transient between the holes.

Seam 5 showed low and very low DST derived permeabilities and a comparatively high permeability from the inter hole permeability curve match which was of moderate quality. This higher permeability was not in the expected direction. In this respect it was similar to Seam 3.

The compressibility-porosity products derived from the curve matches are highly variable and show a complex picture. In the location of holes 1 and 2 the $c.\emptyset$ product lies between 42×10^{-12} Pa^{-1} and 423×10^{-12} Pa^{-1}. This may be thought to be seam dependent. However in location of holes 3, 4 and 5 which are only 700 m distant the values are much higher. Seam 1 here has a $c.\emptyset$ product of 1010×10^{-12} Pa^{-1} compared to the value at the first location of 42×10^{-12} Pa^{-1}. The same applies to Seam 2. In the first location the $c.\emptyset$ product has a value of 244×10^{-12} Pa^{-1} while in the second location the value derived is 1699×10^{-12} Pa^{-1}. The poorer curve matches for seams 3 and 5 at location 2 lead to very high $c.\emptyset$ product values and the question may be asked as to whether the tests were conducted on or adjacent to some structure such as an open fault.

Conclusions

This paper has described a process of determining permeability by a process of DST testing followed by the installation of pressure transducers into the tested well using a novel, efficient and testable method. This is followed by the drilling of an adjacent well and its testing by DST techniques. The DST tests have created adequate pressure pulses to be detected by the sensitive vibrating wire pressure transducers installed in the first hole to enable a match between observed and theoretical behaviour. In one case an additional hole has been drilled and a further DST conducted to achieve an orthogonal test orientation.

The test location is in a complex sub basin with a series of coal seams some of which are separated by coaly shales. The sedimentary geology is relatively straightforward but the area has been warped and both reverse and slip strike faulting exists. The changing stress directions are shown in borehole breakout and in overcore stress measurements.

The permeabilities measured are found to vary in magnitude and direction on a quite local scale. The first site has a generally higher permeability profile with a lower compressibility-porosity product than the second. The major to minor permeability ratio varies from unity to 7.5:1 in the higher permeability areas but in the second location two of the seams exhibit extreme ratios of more than 200:1. These cases are associated with poor pressure transient match between boreholes and very high compressibility-porosity products. This may be a function of local faulting.

The first lesson to be gained from this work is that in structurally complex coals the reservoir characteristics are highly variable. Here inhomogeneity of permeability and anisotropy dominates.

The second lesson is in the development of a highly efficient and low cost technique to extend DST testing with pressure transducer installation to derive directional permeability and compressibility-porosity values.

Finally the DSTs did not produce any pressure pulses in the adjacent strata nor in the momory gauge below the lowest packer. The transducers are now installed for a production trial and interconnection will be determined from long term observations.

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Acknowledgements

The author wishes of acknowledge the contribution of his colleagues from Sigra. Specifically Bruce Neels who helped develop the transducer installation system. Russell Noonan, Edward Cawley and Darryl Smith who installed them and carried out the DST testing. Darryl Smith also assisted in the analysis of the results while John Nooyen helped put together the instrumentation.