KTB sonic logs

Petr Bulant & Luděk Klimeš
Department of Geophysics, Faculty of Mathematics and Physics, Charles University, Ke Karlovu 3, 121 16 Praha 2, Czech Republic,
http://sw3d.cz/staff/bulant.htm, http://sw3d.cz/staff/klimes.htm

Summary

The medium correlation function is of principal importance in refraction travel-time tomographic inversion. To estimate the correlation function in the vertical direction for the Western Bohemia region, we may use the data from sonic-log measurements in the KTB wells. In the KTB Pilot hole, the P-wave and S-wave slownesses were measured to the depth of about 4 km. In the KTB Main hole, the P-wave slowness was measured to the depth of about 9.1 km, but with considerably increased error below the depth of 7.1 km. The well trajectory under 8.6 km is uncertain and the results of the P-wave slowness measurements are not reliable. In some parts of the well, two measurements of the P-wave slowness overlap, which enabled us to estimate the P-wave slowness measurement errors. The S-wave slowness was measured in the KTB Main hole to the depth of about 7.1 km, and in the depth interval between 7.8 km and 8.6 km. The possibilities to estimate the S-wave slowness measurement errors are limited. Measurements of the density were carried out in some depth intervals only, and they are strongly affected by the well defects.

Keywords

Seismic waves, velocity model, medium correlation functions, sonic logs, deep drilling, KTB.

1. Introduction

In order to estimate the relation of a velocity model to the geological structure and, in consequence, to estimate the relation of the synthetic quantities, calculated in the velocity model, to reality, it is important to have an estimate of the medium correlation function (Klimeš, 2002b).

The medium correlation function is of principal importance in refraction travel-time tomographic inversion (Tarantola, 1987; Maurer, Holliger & Boerner, 1998; Klimeš, 2002a), especially when estimating the accuracy of the seismic model, its relation to the geological structure, or the covariance matrix describing the statistics of synthetic travel times.

The medium correlation function for the travel-time tomography should preferably be obtained from travel times. Unfortunately, the deviations of travel times measured during refraction seismic experiments from mean travel times are typically much more sensitive to the horizontal variations of the correlation function than to the vertical variations. For example, Klimeš (2002c) estimated the correlation function of P-wave slowness for the Western Bohemia region in the horizontal direction, but not in the vertical direction. Due to the general structure of the Earth, the correlation function

In: Seismic Waves in Complex 3-D Structures, Report 19 (Department of Geophysics, Charles University, Prague, 2009), pp. 17–38

is considerably anisotropic. Its vertical extent is much smaller with respect to its horizontal extent. We thus need some additional data for estimating the behaviour of the correlation function in the vertical direction. Good sources of these additional data are represented by sonic-log measurements and vertical seismic profiling (VSP) in deep wells.

For the Western Bohemia region, we may use the data from sonic-log measurements and vertical seismic profiling (VSP) in the very deep (9.1 km) KTB well located in Germany, about 25 km from the Czech-German border.

Two wells were drilled at the KTB site, these were the Pilot hole 4001 m deep, and the 9085 m deep Main hole. The Pilot hole wellhead latitude is $49°48'58.8''$, its longitude is $12°7'9.6''$, and its height above the sea level is 513.4 m. The Main hole wellhead latitude is $49°48'58.8''$, its longitude is $12°7'19.2''$, and its height above the sea level is 513.8 m. The two wells are mutually distant about 190 m at the surface, and about 250 m in the depth of 4000 m, see Figure 1.

The results of measurements carried out at the KTB wells are available through the project web site "`http://www.icdp-online.org/sites/ktb`", from which we downloaded all the data files mentioned in this paper.

Drilling of the KTB Main hole was very complicated, the well has several abandoned branches. For more details refer, e.g., to Bram *et al.* (1995).

In the following text, we speak about so called *logging depth*, by which we understand the distance along the well, sometimes also called cable length. The *true vertical depth* (TVD) in both wells of the KTB site is measured from the surface starting point of the Main hole located 513.8 m above sea level, and it is positive downwards. The logging depth 0 m in the Main hole corresponds to TVD 0.1524 m. The Pilot hole has starting point located 513.4 m above sea level, and the logging depth 21 m in the Pilot hole corresponds to TVD 0.7308 m.

In this paper "~" in file URLs stands for
"`http://www.icdp-online.org/sites/ktb/data/logging`".

2. Well trajectories

The Pilot hole inclines slightly towards North, resulting in approximately 200 m of horizontal shift over the 4000 m depth interval. Two files describing the KTB Pilot hole trajectory can be found at the KTB web page. These are "`~/tvd/vb1/00214001.htm`" containing the true vertical depth (TVD) recorded with a step of 1 m in logging depth, and "`~/ori/vb1/00214001.htm`" containing the east-west (EW) and north-south (NS) horizontal well coordinates recorded with the same step of 1 m in logging depth. In Figure 1, EW corresponds to the East coordinate and NS corresponds to North coordinate.

The Main hole is almost vertical to the depth of about 7500 m, and then it inclines towards North-East. Three files describing the KTB Main hole trajectory can be found at the KTB web page. These are "`~/bgl/hb1/complete.htm`", "`~/tvd/hb1/00009080.htm`" and "`~/ori/hb1/86409068.htm`". File "`complete.htm`" contains all the three coordinates of the well in the form of west-east (WE), south-north (SN), and true vertical depth (TVD), recorded with the step of half a feet along the well from 0 to 8633.3076 metres. In Figure 1, WE corresponds to the North coordinate and SN corresponds to East coordinate. File "`00009080.htm`" contains TVD from 0 to

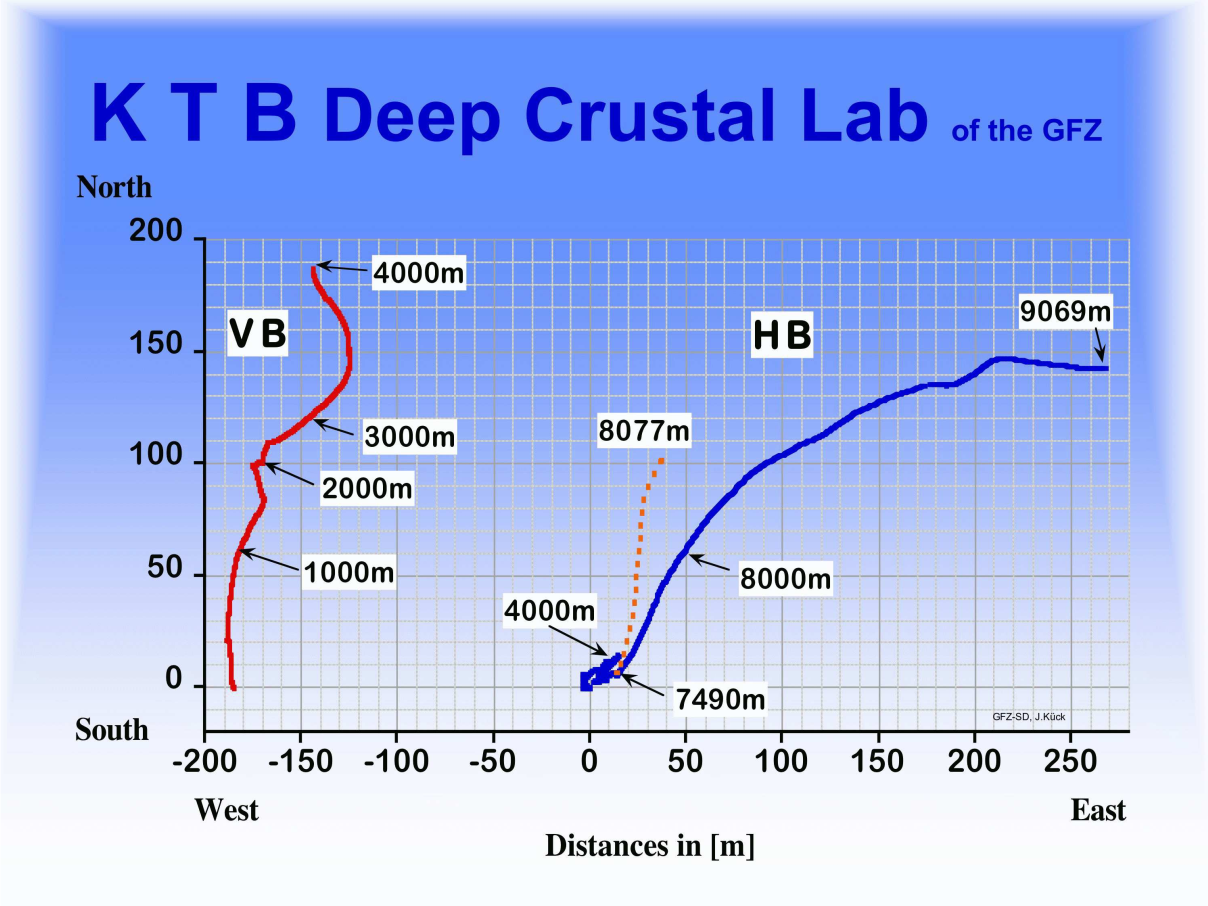

Figure 1. The surface projection of the trajectories of the KTB Pilot hole (VB) and of the KTB Main hole (HB), downloaded from "`http://www.icdp-online.org/sites/ktb/images/KTB%20horzintal%20projection.jpg`". The dotted line shows the part of the well which had to be abandoned due to the drill bit stuck.

9080 metres with the step of one metre. File "`86409068.htm`" contains east-west (EW) and north-south (NS) coordinates for the logging depths 8640 to 9068 m. In Figure 1, EW corresponds to the East coordinate and NS corresponds to North coordinate.

Because the KTB Main hole was drilled nearly vertical to 7500 m, only below the 7500 m the logging depth and the TVD differ each from other. Unfortunately, in the logging depth of ≈8623 m, files "`complete.htm`" and "`00009080.htm`" do not match each other. File "`complete.htm`" displays TVD=8581.0 m, and file "`00009080.htm`" displays TVD=8574.8 m. Next point in file "`00009080.htm`" is in logging depth 8640 m and it displays TVD=8576.2 m. File "`86409068.htm`" again does not match with the file "`complete.htm`", which displays WE=134.00 m and SN=181.66 m in the logging depth of 8633.3076 m, while file "`86409068.htm`" displays EW=176.30 m and NS=135.35 m in the logging depth of 8640 m. See Table 1 for comparison of the files.

In the description of the logging data "`~/readme.htm`", one can read that "below 8640 m the information about the well geometry is missing".

A picture of a vertical projection of the wells can be found at "`http://www.icdp-online.org/sites/ktb/images/KTB%20horzintal%20projection.jpg`", see Figure 1.

logging depth (m)	"complete.htm" WE (m)	SN (m)	TVD (m)	"00009080.htm" TVD (m)	"86409080.htm" EW (m)	NS (m)
8623.0967	133.37	178.33	8581.00			
8623.0000				8574.80		
8633.3076	134.00	181.66	8590.70			
8640.0000				8576.20	176.30	135.35

Table 1. Coordinates of the trajectory of the KTB Main hole recorded in files "`complete.htm`", "`00009080.htm`" and "`86409080.htm`". Compare the values of TVD in files "`complete.htm`" and "`00009080.htm`" in the logging depth around 8623 m. Compare also the values of WE, SN, EW and NS in files "`complete.htm`" and "`86409080.htm`" in the logging depths 8633.3076 m and 8640.000 m.

3. P-wave and S-wave slownesses and density

Drilling and logging of the KTB Main hole was performed in several steps. In each step, the well was drilled to a certain depth, then the drilled part was logged, and then the casing was put into the well. In the next step, the well was drilled further, uncased part was logged, and then cased. Sonic logging in the KTB well thus in fact consists of several independent sonic log measurements in different well segments in different depth ranges and in different times. Below we will assign the segments with numbers 1 to 8 according to the 8 files with sonic logs available at the KTB web page, but we keep in mind that the data in the individual files are usually merged from several original KTB data files. See Table 2 for the description of the segments.

Segment No	P-wave slowness recorded in logging depths (m)	S-wave slowness recorded in logging depths (m)	density recorded in logging depths (m)
1	290.0172 - 2999.9941	290.0172 - 2999.9941	
2	2999.9941 - 4509.9731	2999.9941 - 4509.9731	2999.9941 - 4509.9731
3	4449.9277 - 6015.0757	4449.9277 - 6015.0757	4449.9277 - 6017.0566
4	6011.4180 - 7163.1050	6011.4180 - 7163.1050	6020.1050 - 7135.2158
5	6900.0625 - 8096.4023		7104.2783 - 8099.9077
6	7794.9551 - 8640.0137	7802.4229 - 8637.7275	
7	8503.0059 - 9037.0156		
8	9043.1113 - 9085.0215	9043.1113 - 9085.0215	9040.0635 - 9085.0215

Table 2. Overview of the individual segments of the KTB Main hole, in which the sonic logging took place, and of the logging depths, for which the measured values of P-wave slowness, S-wave slowness and density are available.

The P and S-wave propagation slownesses in the well were measured by sonic logging with the depth step of 0.5 feet (0.1514 m). Three different sonde types were run in the KTB well. To a logging depth of 7200 m (segments 1-4) the well was logged with digital recording sonic tools, Sonic Digital Tool (SDT) and Dipole Shear Sonic Imager (DSI). The error of these tools is commonly considered to be below 2 microseconds per feet (≈6.6 microseconds per meter). The DSI tool contains 8 receivers placed within 3.5 feet (≈1.06 m), and it thus measures integrally over the 1 meter distance. For hostile conditions in the deeper part of the well (segments 5-8), Hostile Sonic Logging Tool (HSLT) was used. Well logging data have been corrected for well effects, e.g., breakout effects, mud resistivity effects and temperature effects, standardization to a reference well diameter 8" or 8 1/2". Data below 8503 m (segments 7 and 8) are corrected only for depth. Well corrections of the logging data are based upon inferences due to measurements, empirical relationships and assumptions, which by nature of their complexity are not infallible, and KTB does not warrant the accuracy, correctness or completeness of this data.

The casing was usually not installed to the whole drilled part of the well, a short deepest part was usually left uncased. These parts of the well were thus logged twice, first time shortly after the well segment was drilled, and second time when the next well segment was drilled. Before the second logging, this part of the well was influenced by the drilling tool moving many times up and down, by the drilling mud pumped under high pressure, etc. The horizontal stress was affecting the shape of the well, and so called "breakouts" appeared. Even though the well logging data have been corrected for well effects, in each sonic log we may thus assume that the uppermost part of the logged well segment is the part which is most influenced by the above described processes, while the lowest part is the less influenced. The information from the two measurements in the part of the well which was logged twice is thus a valuable source of the information about the measurement errors caused by drilling works in the formation.

According to the description of the logging data (file "`~/eblmremk.htm`"), the interval below 6020 metres (well segments 4 to 8) is characterized by considerable well enlargements and a rugose wall. Therefore, despite appropriate corrections, the data can still be affected in certain zones. This is more or less valid for all parameters but especially for those which are produced by pad-type tools. Particular attention must be paid to the fact that only cased well data exist in the intervals 6840 to 7795 m in the well segment 5, and 8510 to 9038 m in the well segment 7.

3.1. P-wave slowness

The P-wave slowness in the Main hole was measured in all the 8 well segments, see Figure 2 for all the values displayed in a single graph, and compare with the values measured in the Pilot hole displayed in Figure 3. Figures 4 to 7 show the details of the depth sections of the Main hole where two measurements overlap in well segments 2-3, 3-4, 4-5 and 5-6 respectively.

We have plotted correlations of the P-wave slownesses in well segments 2 and 3, and as there was no peak in the graph, we concluded that there is no correlation of the slownesses, and the differences between the slownesses are thus only the measurement errors.

Figure 8 displays the autocorrelations of the differences of the P-wave slownesses measured in well segments 2 and 3. We can see that the only difference between the two measurements of P-wave slowness is the random difference with the standard deviation of $8.1\,\mu$s/m. The shape of the peak is close to the triangle with its base twice larger than the sonic tool. It is thus obvious that the source of the difference is not moving with the sonic tool, that it is fixed to the well.

Figure 9 displays the autocorrelations of the differences of the P-wave slownesses measured in well segments 4 and 5. We observe the values of P-wave slowness in segment 5 systematically higher by $9.0\,\mu$s/m with respect to segment 4, and the random difference with the standard deviation of $19.4\,\mu$s/m.

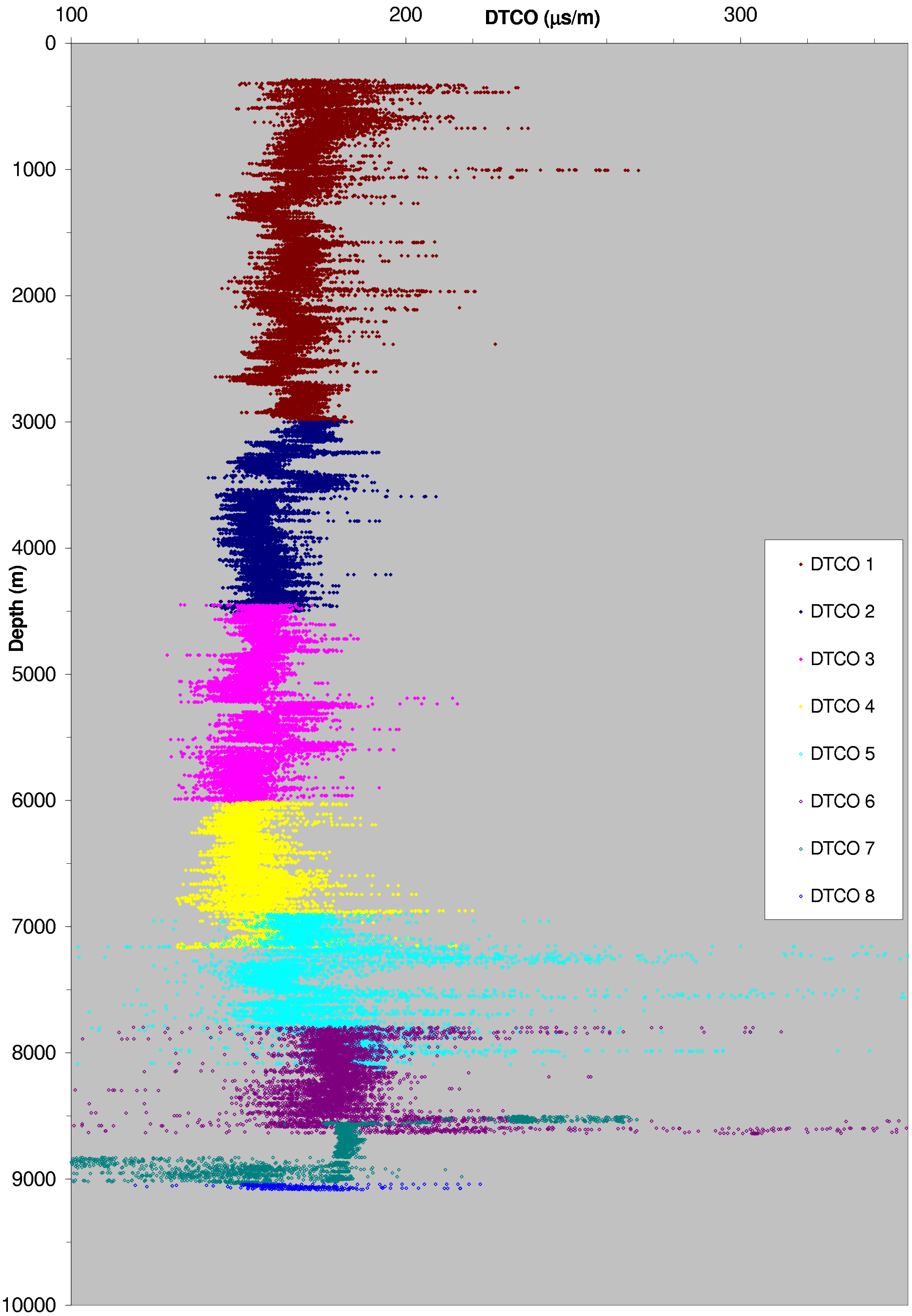

Figure 2. P-wave propagation slowness (DTCO) in all the 8 segments of the KTB Main hole plotted in dependence on logging depth (Depth). Logging depth corresponds approximately to true vertical depth in the interval from 0 m to 7500 m, at logging depth 8633 m the true vertical depth is about 8591 m. Note that the segments 1 to 4 were measured with the SDT and DSI tools, segments 5 to 8 with the HSLT tool. Also note that the measurements in segments 5 and 7 were performed in a cased well (see the constant slowness $\approx 180\,\mu$s/m in logging depths around 8700 m, this value corresponds to the slowness in the steel).

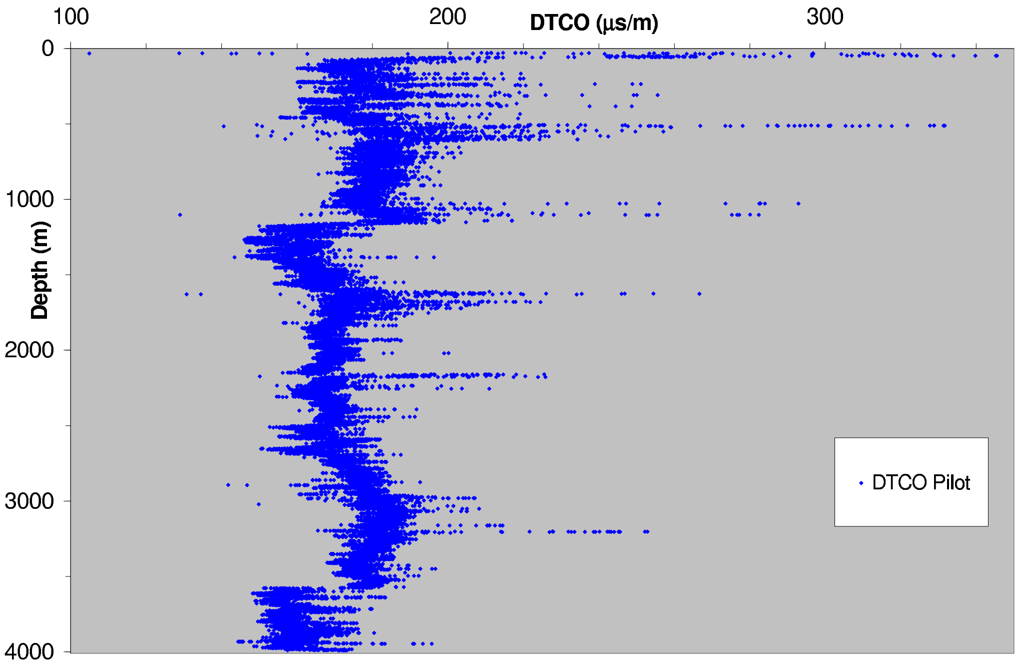

Figure 3. P-wave propagation slowness (DTCO) in the KTB Pilot hole plotted in dependence on logging depth (Depth). Logging depth 20 m corresponds approximately to true vertical depth 0 m, at logging depth 4000 m the true vertical depth is about 3970 m.

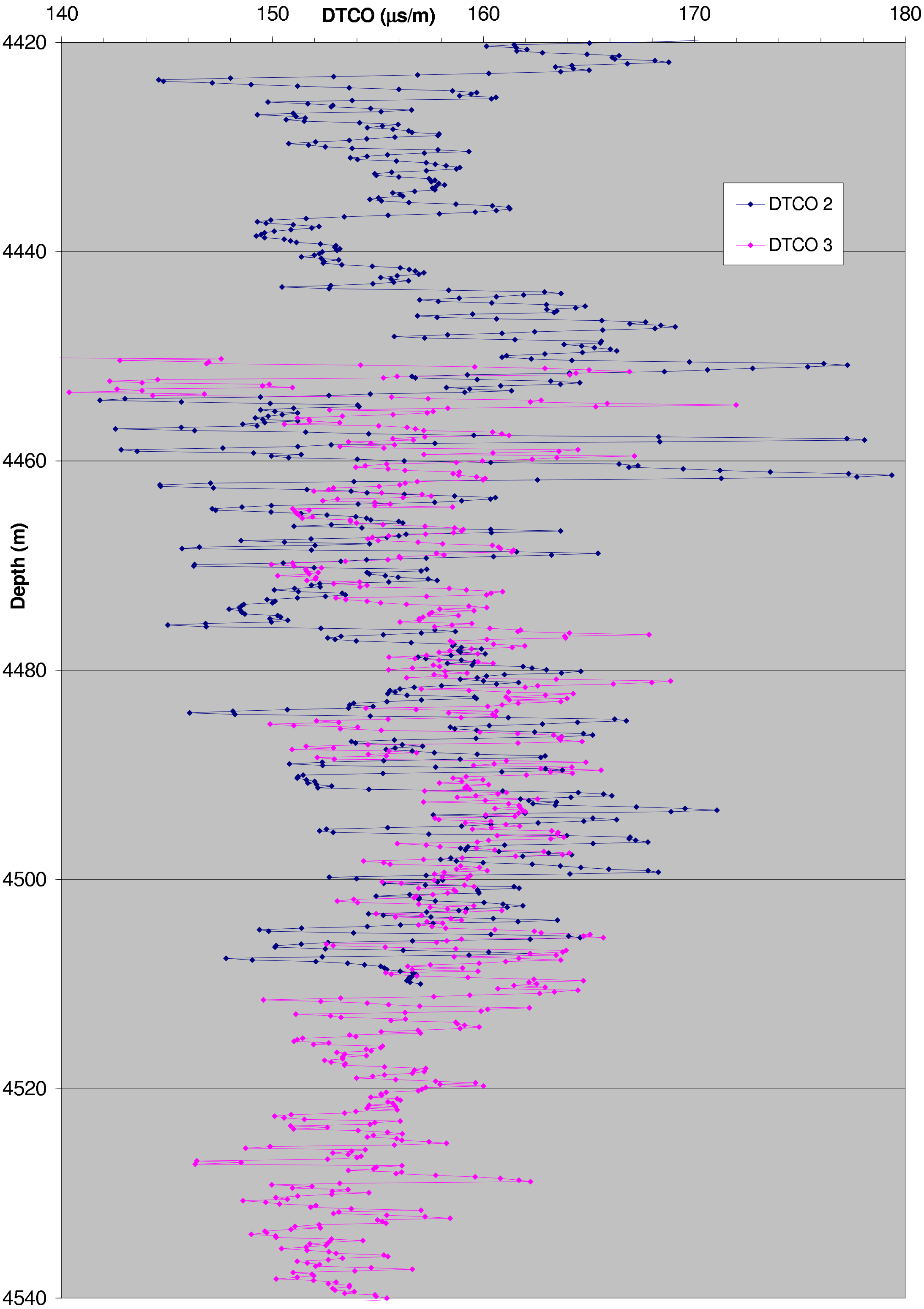

Figure 4. P-wave propagation slowness (DTCO) in the part of the Main hole where the measurements in segments 2 and 3 overlap.

Figure 5. P-wave propagation slowness (DTCO) in the part of the Main hole where the measurements in segments 3 and 4 overlap.

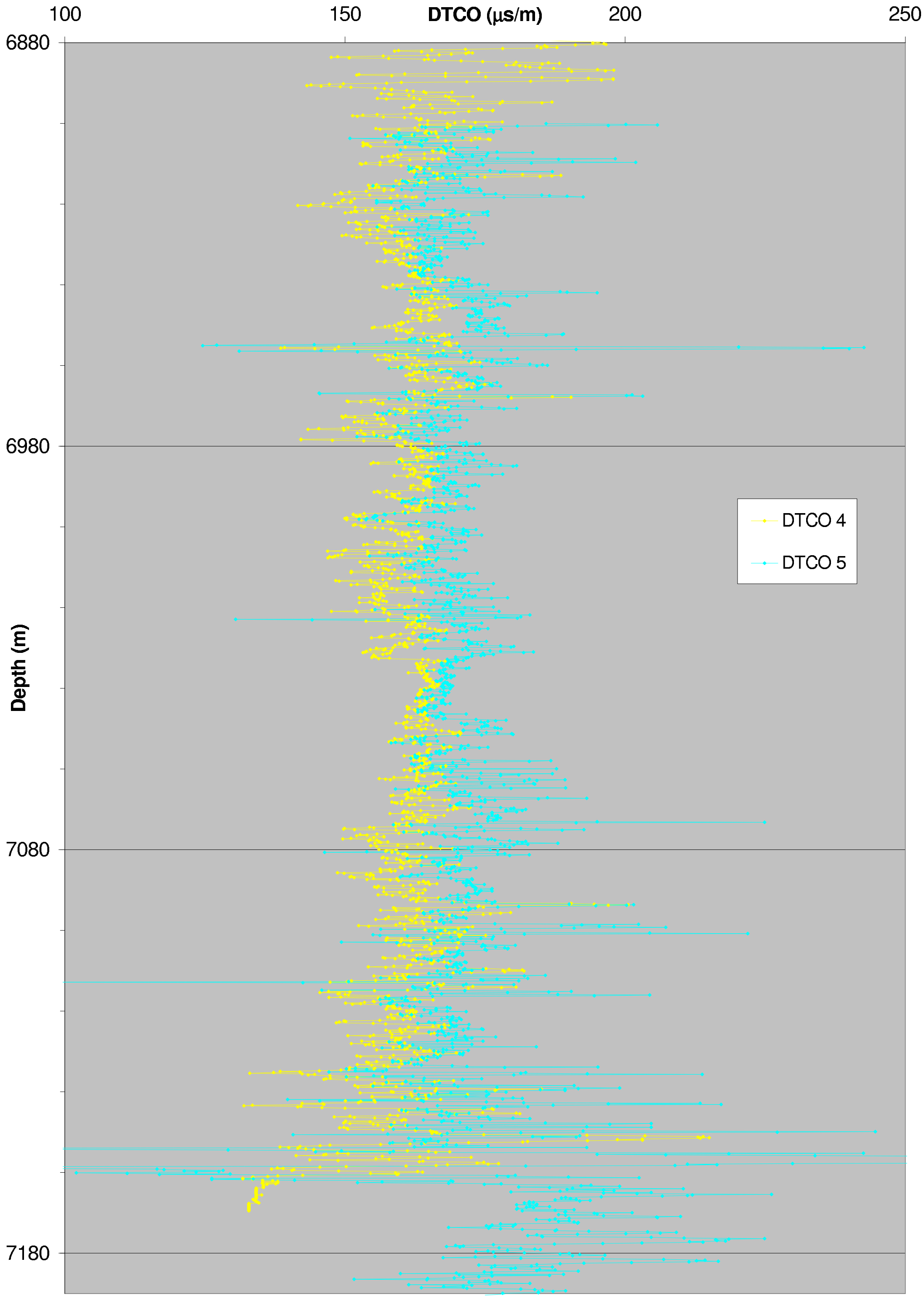

Figure 6. P-wave propagation slowness (DTCO) in the part of the Main hole where the measurements in segments 4 and 5 overlap.

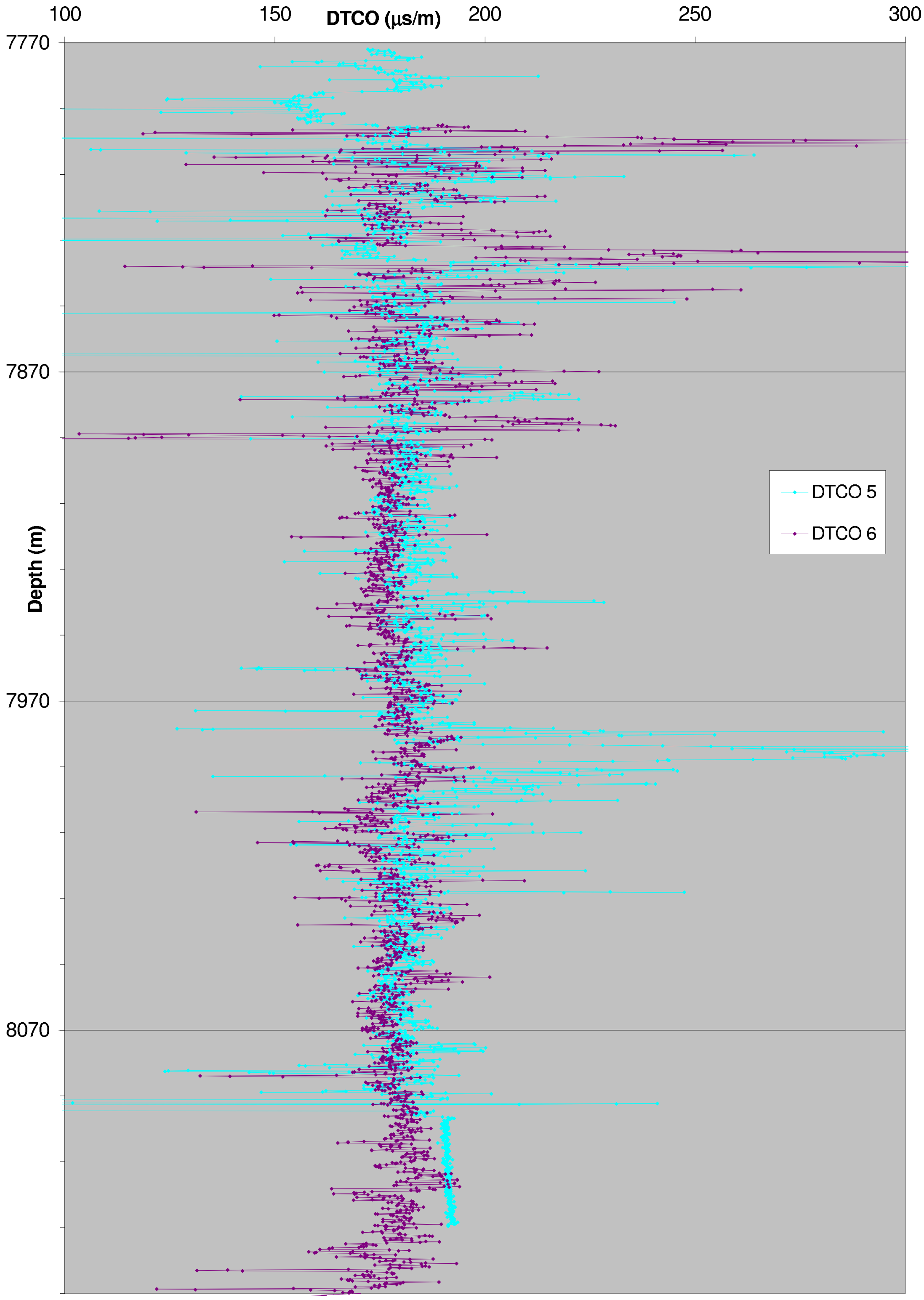

Figure 7. P-wave propagation slowness (DTCO) in the part of the Main hole where the measurements in segments 5 and 6 overlap.

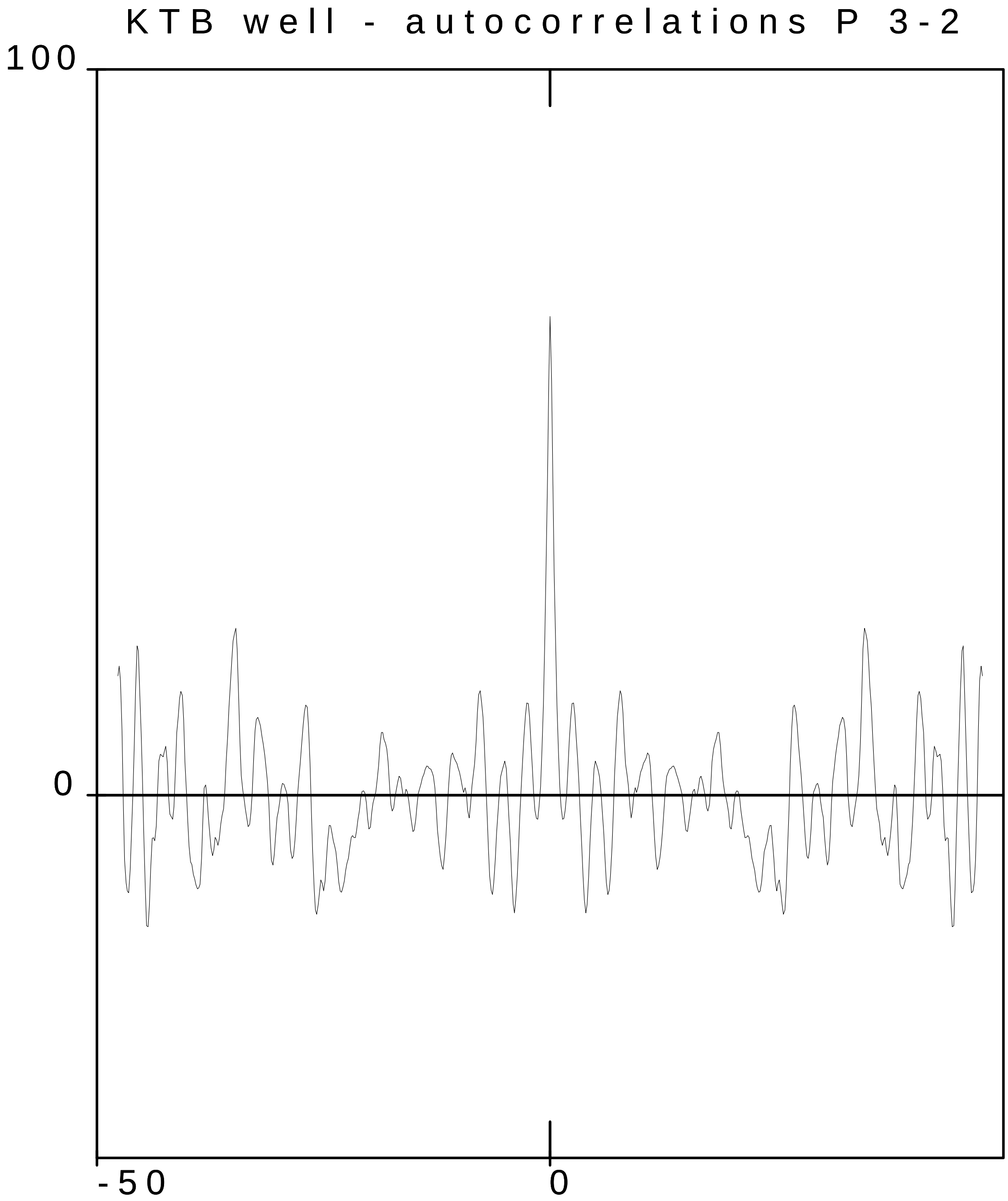

Figure 8. Autocorrelations of the differences between the P-wave propagation slownesses measured in well segments 2 and 3 in $(\mu s/m)^2$. We can see that the only difference between the two measurements of P-wave slowness is the random difference with the standard deviation of $8.1\,\mu s/m$. The shape of the peak is close to the triangle with its base twice larger than the sonic tool. It is thus obvious that the source of the difference is not moving with the sonic tool, that it is fixed to the well.

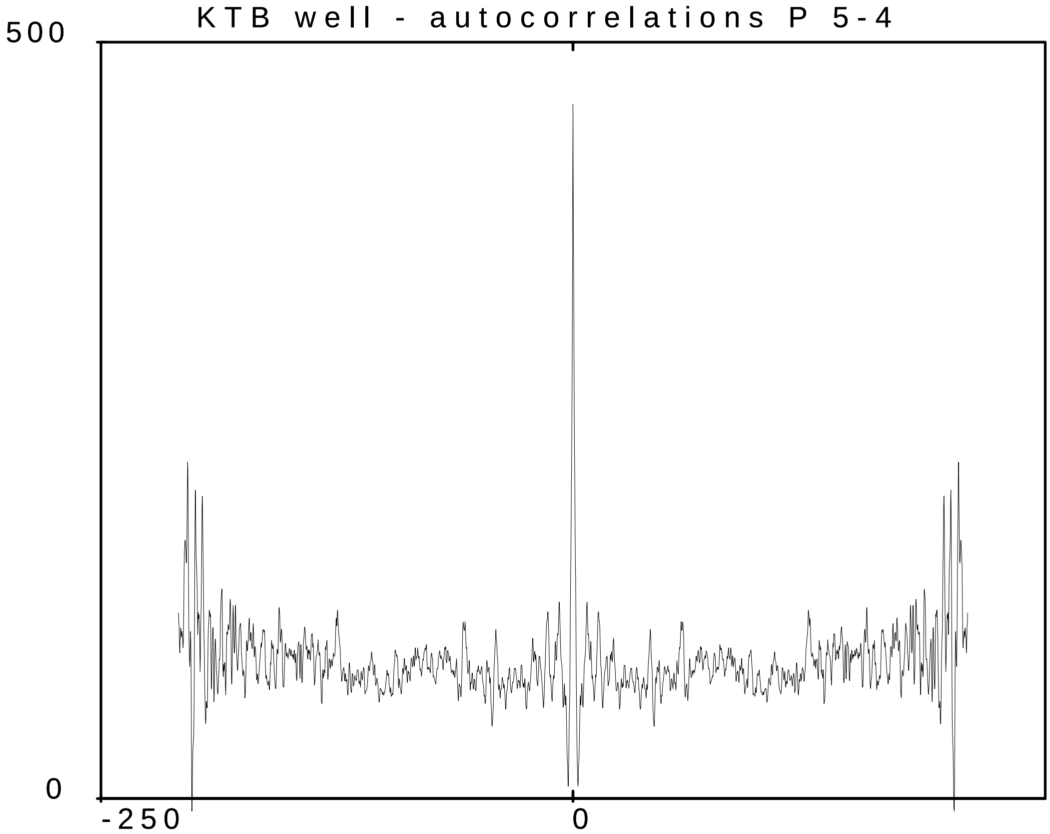

Figure 9. Autocorrelations of the differences between the P-wave propagation slownesses measured in well segments 4 and 5 in $(\mu\text{s/m})^2$. We observe the values of P-wave slowness in segment 5 systematically higher by $9.0\,\mu$s/m with respect to segment 4, and the random difference with the standard deviation of $19.4\,\mu$s/m.

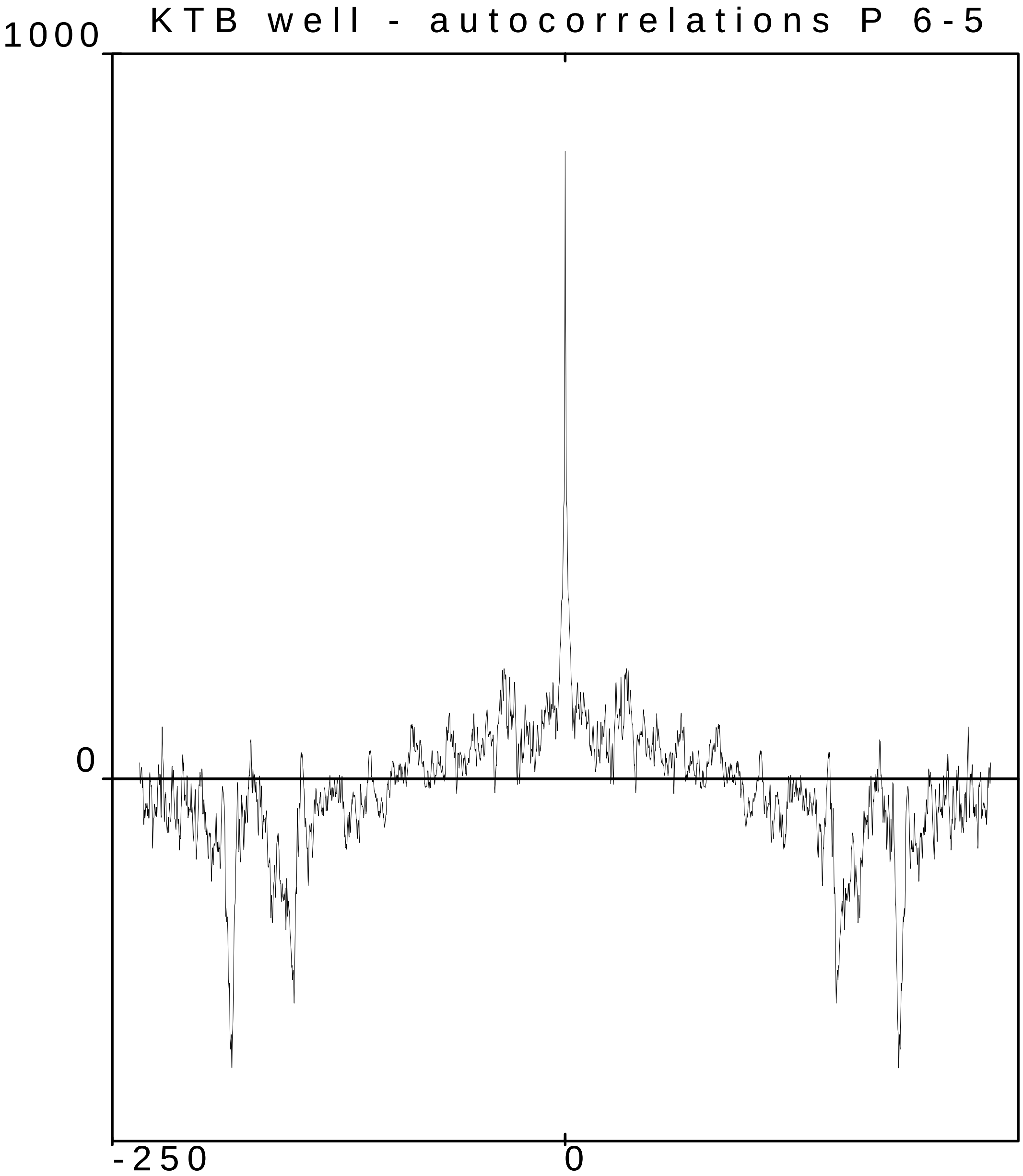

Figure 10. Autocorrelations of the differences between the P-wave propagation slownesses measured in well segments 5 and 6 in $(\mu\text{s/m})^2$. We observe the values of P-wave slowness in segment 5 systematically higher by $9\,\mu\text{s/m}$ with respect to segment 6, and the random difference with the standard deviation of $28.0\,\mu\text{s/m}$.

Figure 10 displays the autocorrelations of the differences of the P-wave slownesses measured in well segments 5 and 6. We observe the values of P-wave slowness in segment 5 systematically higher by $9\,\mu\text{s/m}$ with respect to segment 6, and the random difference with the standard deviation of $28.0\,\mu\text{s/m}$.

3.2. S-wave slowness

The S-wave slowness in the Main hole was measured in the segments 1 to 4, 6 and 8, see Figure 11. For comparison, the values of S-wave slowness measured in the Pilot hole are shown in Figure 12. Figures 13 and 14 show the details of the sections of the Main hole where two measurements overlap.

Figure 15 displays the autocorrelations of the differences of the S-wave slownesses measured in well segments 2 and 3. We observe the values of S-wave slowness in segment 3 systematically higher by 11.5 μs/m with respect to segment 2, and the random difference with the standard deviation of 13.2 μs/m.

3.3. Density

The density was measured in the well segments 2-5 and 8, and it does not vary significantly along the well, se Figure 16. Note that the density measurement is very sensitive to the defects in the well walls, see Figure 17 for an example.

Acknowledgements

Logging data were obtained under grants RG8604, RG8803 and RG 9001 of the Federal Ministry of Research and Technology and provided by the KTB Project Management, Geological Survey of Lower Saxony, Germany.

Our research has been supported by the Grant Agency of the Czech Republic under Contract 205/07/0032, by the Ministry of Education of the Czech Republic within research project MSM0021620860, and by the members of the consortium "Seismic Waves in Complex 3-D Structures" (see "http://sw3d.cz").

References

Bram, K., Draxler, J., Hirschmann, G., Zoth, G., Hiron, S. and Kuhr, M. (1995): The KTB Borehole - Germany's Superdeep Telescope into the Earth's Crust. *Oilfield Review*, **7**, 4-22.

Klimeš, L. (2002a): Application of the medium covariance functions to travel–time tomography. *Pure appl. Geophys.*, **159**, 1791–1810, online at "http://sw3d.cz".

Klimeš, L. (2002b): Correlation functions of random media. *Pure appl. Geophys.*, **159**, 1811–1831, online at "http://sw3d.cz".

Klimeš, L. (2002c): Estimating the correlation function of a self–affine random medium. *Pure appl. Geophys.*, **159**, 1833–1853, online at "http://sw3d.cz".

Maurer, H, Holliger, K. & Boerner, D.E. (1998): Stochastic regularization: Smoothness or similarity?. *Geophys. Res. Lett.*, **25**, 2889–2892.

Tarantola, A. (1987): Inversion of travel times and seismic waveforms. In: Nolet, G. (ed.): *Sesmic Tomography*, pp. 135–157, D. Reidel Publ. Co., Dordrecht.

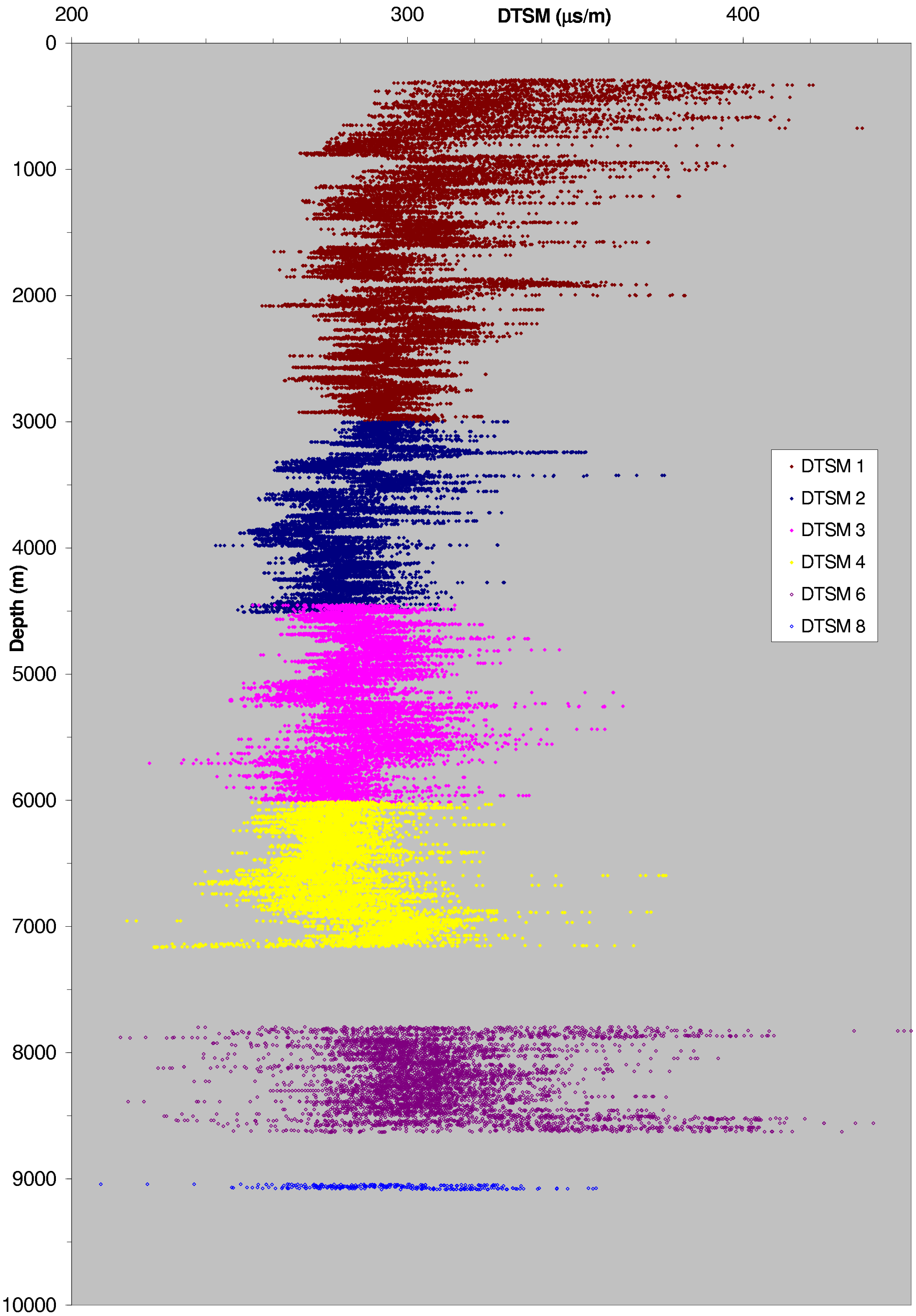

Figure 11. S-wave propagation slowness (DTSM) in all the segments of the KTB Main hole where DTSM was measured (segments 1-4, 6, 8). Note that the segments 1 to 4 were measured with the SDT and DSI tools, segments 6 and 8 with the HSLT tool.

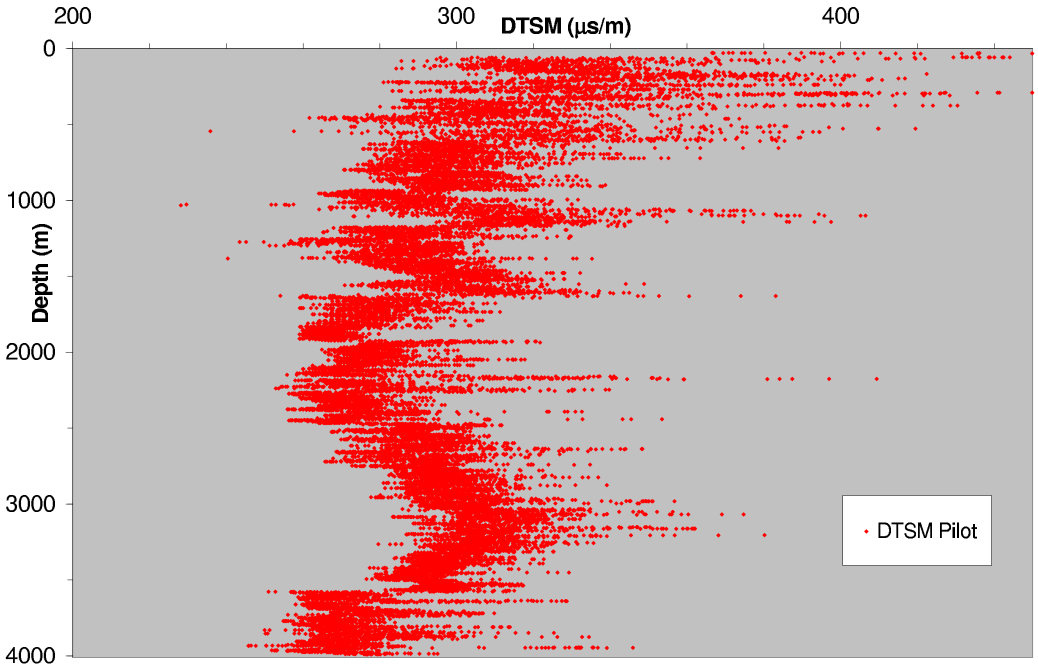

Figure 12. S-wave propagation slowness (DTSM) in the KTB Pilot hole.

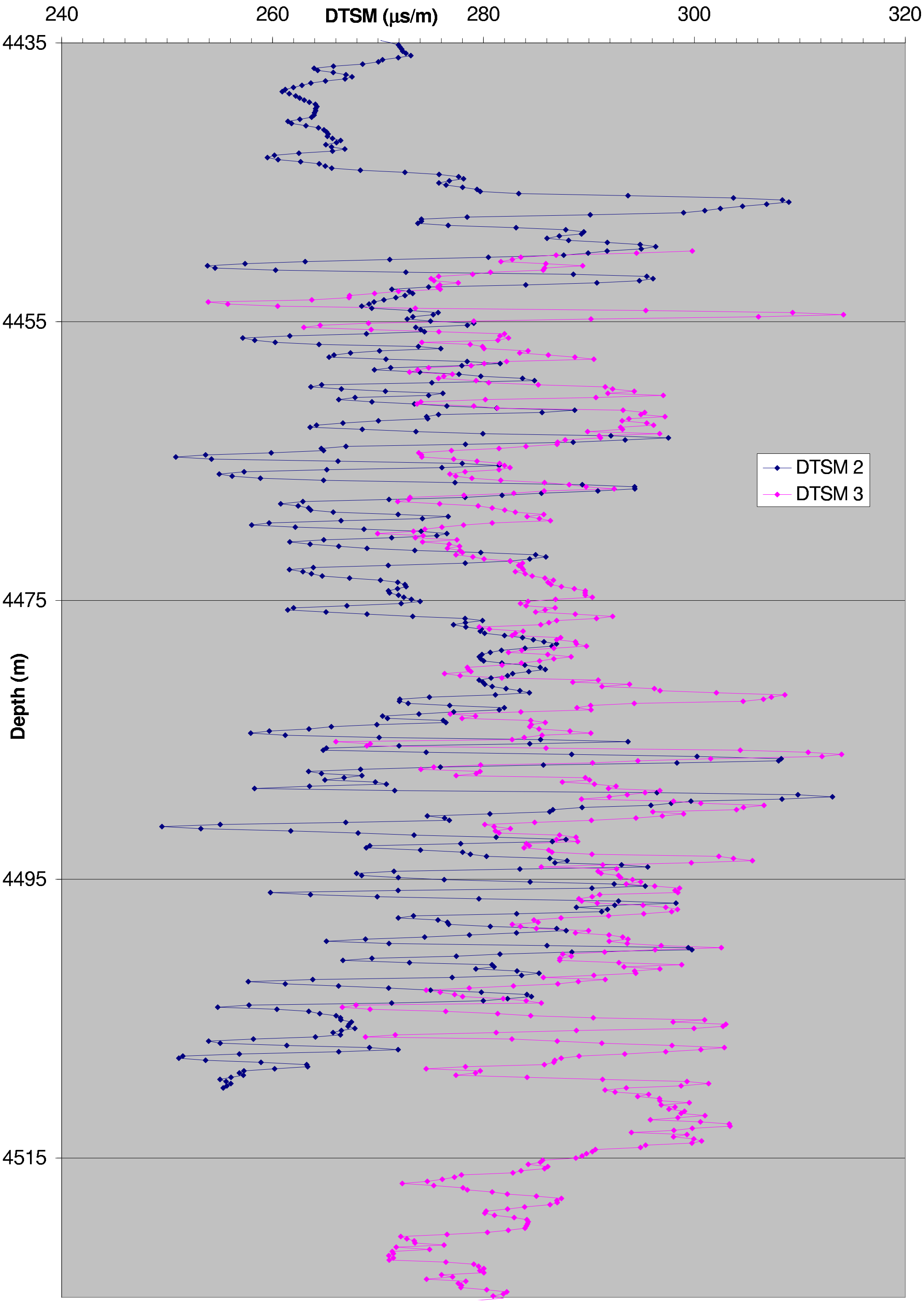

Figure 13. S-wave propagation slowness (DTSM) in the part of the KTB Main hole where the measurements in segments 2 and 3 overlap.

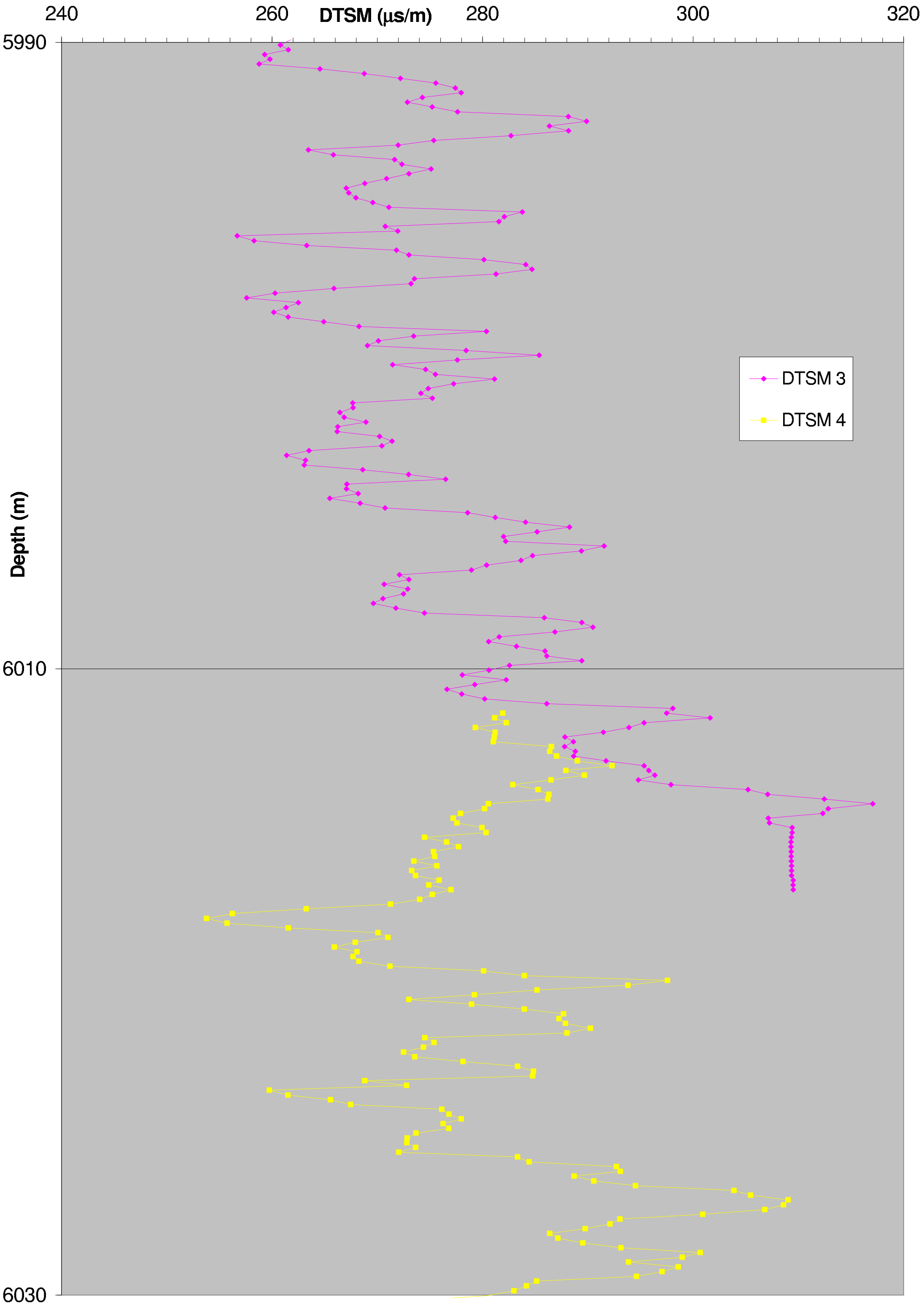

Figure 14. S-wave propagation slowness (DTSM) in the part of the KTB Main hole where the measurements in segments 3 and 4 overlap.

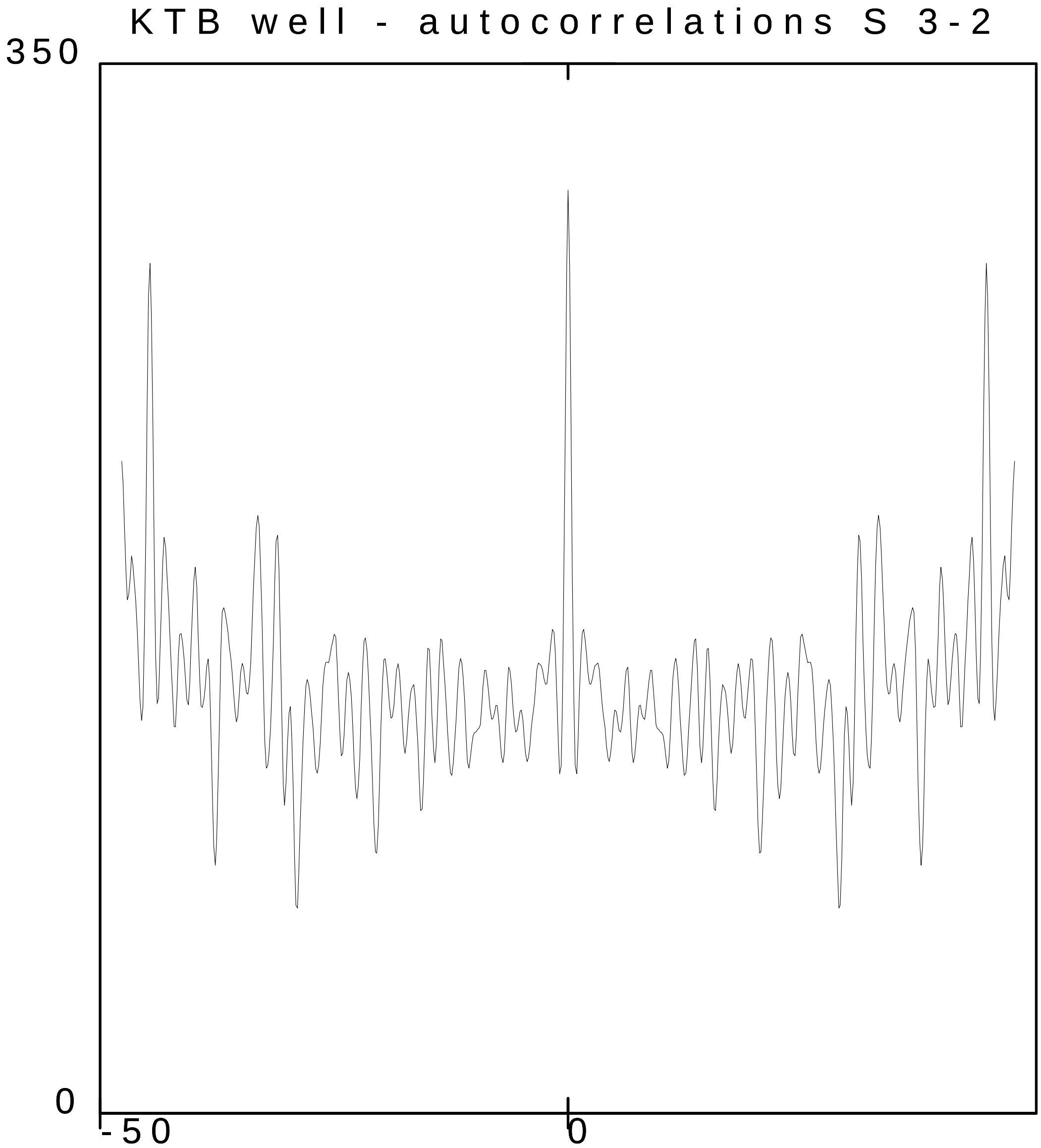

Figure 15. Autocorrelations of the differences between the S-wave propagation slownesses measured in KTB Main hole segments 2 and 3 in $(\mu s/m)^2$. We observe the values of S-wave slowness in segment 3 systematically higher by $11.5\,\mu s/m$ with respect to segment 2, and the random difference with the standard deviation of $13.2\,\mu s/m$.

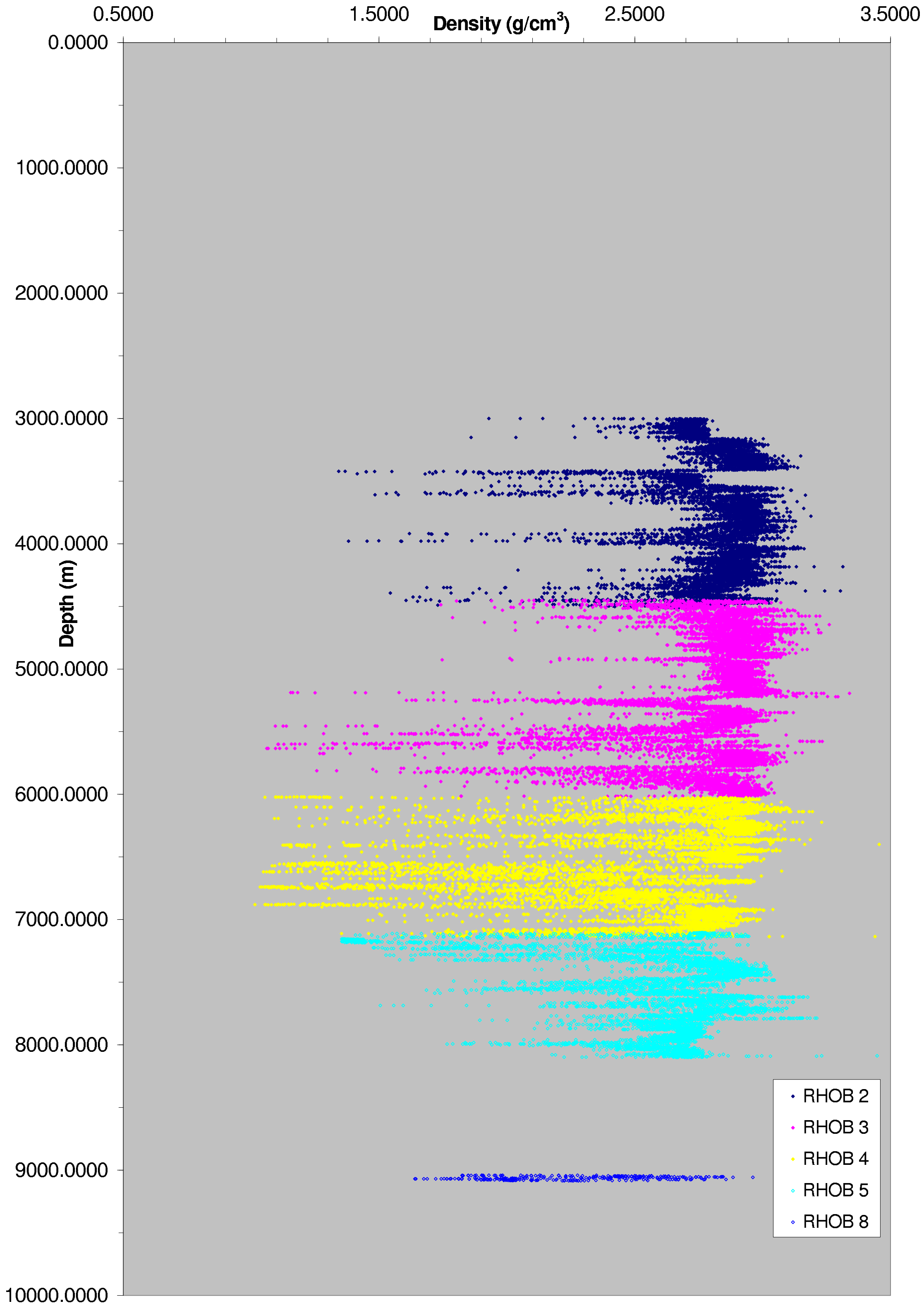

Figure 16. Density measured in the KTB Main hole (segments 2-5 and 8). The density does not vary significantly along the well, but the values are very sensitive to the damages (enlargements) of the well walls, see Figure 17.

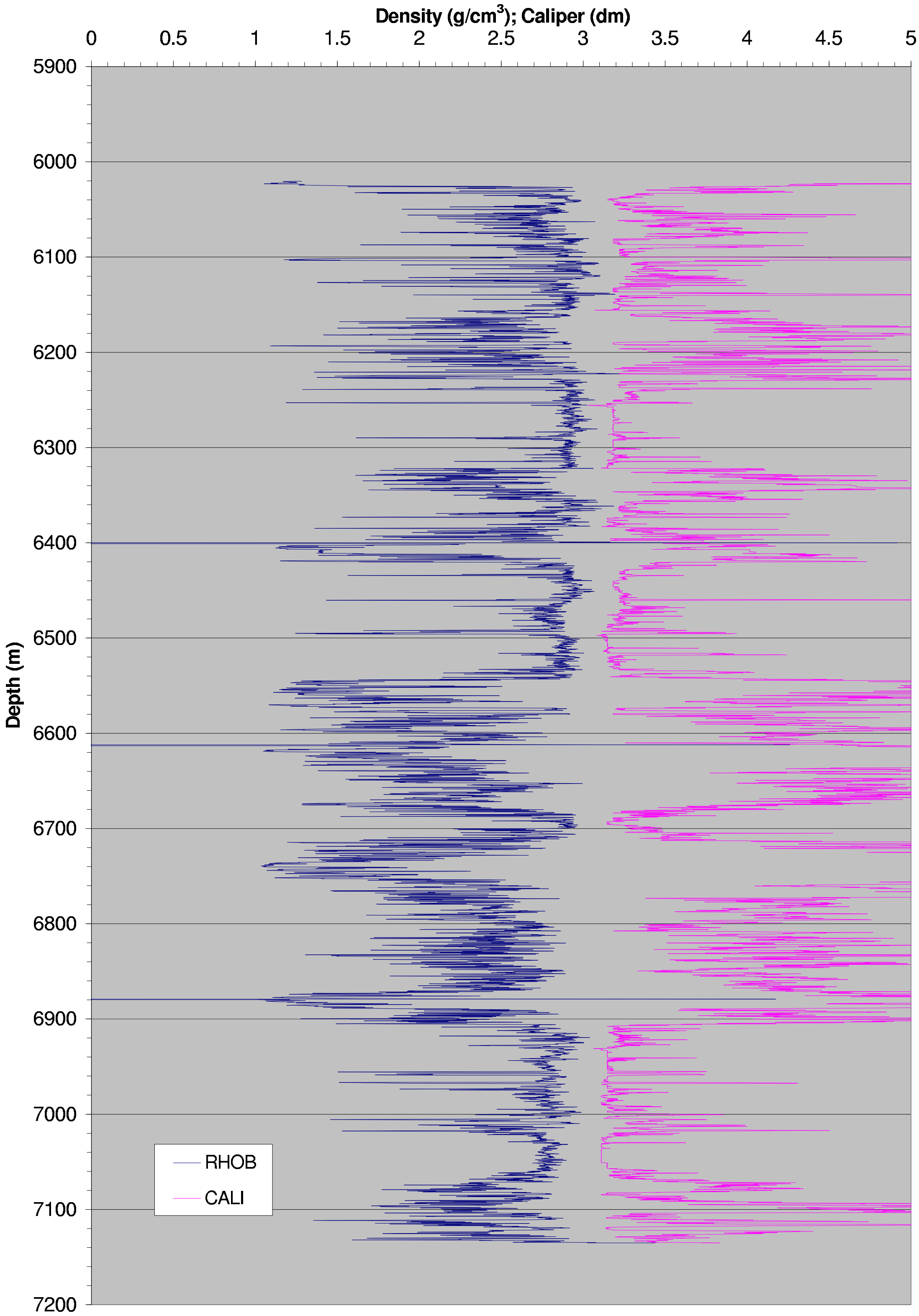

Figure 17. A detail of the density (RHOB) profile in the KTB well segment 4, displayed together with the values of the 1-arm caliper (CALI), i.e. with the width of the well. The correlation between the well enlargements and low density values is clearly visible.