Stress sensitivity of seismic and electric rock properties of the upper continental crust at the KTB.

A. Kaselow, K. Becker, and S. A. Shapiro

email: *kaselow@geophysik.fu-berlin.de*

keywords: *Stress Sensitivity, Pressure, Velocities*

ABSTRACT

We test the hypothesis that the general trend of P-wave and S-wave sonic log velocities and resistivity with depth in the pilot hole of the KTB site, Germany, can be explained by the progressive closure of the compliant porosity with increasing effective pressure. We introduce a quantity θ_c characterizing the stress sensitivity of the mentioned properties. A simultaneously conducted analyzis of the downhole measurements revealed that θ_c for elastic and electrical properties of the in-situ formation coincide. Moreover, it is 3.5 to 4.5 times larger than the averaged stress-sensitivity obtained from core samples. We conclude that the hypothesis mentioned above is consistent with both data sets. Moreover, since θ_c corresponds approximately to the inverse of the effective crack aspect ratio, larger in-situ estimates of θ_c might reflect the influence of fractures and faults ($> 10^{-1}$ m) on the stress-sensitivity of the crystalline formation in contrast to the stress-sensitivity of the nearly intact core samples. Finally, because the stress sensitivity is directly related to the elastic non-linearity we conclude that the non-linearity of the KTB rocks is significantly larger in-situ than in the laboratory.

INTRODUCTION

In this work we present an analyzis of the dependence of P- and S-wave velocity and electrical resistivity of metamorphic crustal rocks on differential pressure (depth) at the German Continental Deep Drilling Site (KTB) down to 4000 m depth. We involve downhole sonic and deep lateral resistivity log data from the pilot hole and laboratory derived stress-dependent P- and S-wave velocities into our analyzis. The used rock samples were also recovered from the KTB pilot hole.

The pilot (4000 m) and the main borehole (9101 m) and the surrounding area of the KTB site have been the subject of geoscientific research for more than a decade (Emmermann and Lauterjung, 1997). The project was dedicated to understand the geological, hydrogeological and geophysical settings of the upper continental crust. The suite of geophysical monitoring covers downhole measurements, core and cutting analyzes, potential field analyzes, VSP, and numerous 2D and 3D seismic surveys. The hydraulic system of the drilled crustal section which shows many prominent hydraulically conducting fracture systems and hydrostatic pore pressure down to the final depth of the pilot hole was tested by pumping and injection tests. A comprehensive summary of the KTB research and further references are given in Haak and Jones (1997). In summary the results from the KTB research project provide a huge and unique data base to obtain a deeper insight into the geoscientific properties of the upper continental crust.

The goal of this work is to use sonic downhole velocities, resistivity log and ultrasonic laboratory data from rocks of the KTB pilot hole down to 4000 m depth in order to (a) test our hypothesis that the general depth trend of the mentioned properties results from compliant pore space closure with increasing effective pressure (i.e., depth) and (b) to give a quantitative measure for the stress sensitivity of the KTB rocks. Therefore we use the Stress-Sensitivity-Approach for isotropic rocks as introduced by Shapiro (2003) and the extension of the approach to the stress sensitivity of electrical resistivity (Kaselow and Shapiro, 2004).

THE DATA SETS

The laboratory measurements of P- and S-wave velocities were conducted on dry cubic samples in a true-tri-axial pressure apparatus up to 600 MPa confining pressure. Three P- and six corresponding S-wave velocities were simultaneously measured in three orthogonal directions. The measurement coordinate system was oriented with respect to the macroscopically visible foliation plane and lineation elements. For details about the measurements see Kern and Schmidt (1990); Kern et al. (1991, 1994). These laboratory observations showed a clear correlation between the lithology and seismic velocities (e.g., Kern et al., 1991).

According to Emmermann and Rieschmüller (1990) the rocks of the KTB pilot hole can lithologically be subdivided into nine units. In agreement with the laboratory data the sonic P- and S-wave profiles shown in Fig.(1) indicate a correlation between the lithological units and wave velocities. The correlation seems to be stronger for P-wave velocities than for S-waves, especially in the depth range above 1610 m (unit 1-3) and below 3575 m (unit 9).

The resistivity profile of the KTB location was investigated by numerous researchers. A comprehensive summary is given by ELEKTB-Group (1997). They found that the mean resistivity (in logarithmic scale) increases almost linearly with depth and shows practically no correlation with lithology. Moreover, some very pronounced low resistivity anomalies could be identified which are also clearly not linked to lithology.

The profile interpretation that resistivity and lithology are not correlated was confirmed by laboratory measurements (Rauen, 1991). An observed decrease of resistivity with increasing recovery depth is assumed to be caused by pressure release effects during and after recovery. The influence of pressure on the resistivity was investigated by Huenges et al. (1990); Nover and Will (1991); Duba et al. (1994); Nover et al. (1995). Although most samples showed an expected increasing resistivity with increasing applied pressure some samples showed the opposite behaviour. Their decreasing resistivity with increasing pressure was interpreted by Duba et al. (1994) as the result of reconnection of metallic bound that might have been disrupted by pressure release during core recovery. Long-term observations ($>$300-600 h) on anomalous samples showed that some of them returned to normal behaviour. This was interpreted by Rauen et al. (1994) as caused by pressure induced internal redistribution of fluids. Thus the anomalous pressure effect seems to indicate the reconnection of metallic bounds and the dominance of electrolytic conductivity.

METHOD

In a first step we assume that the KTB rock pile can be represented as a homogeneous isotropic porous medium. Thus we neglect the influence of different lithologies on the logs. This is a rough approximation since the KTB rocks are known to be anisotropic and at least P-wave logging shows a correlation between velocity and lithology. However, this correlation seems to be remarkably weaker for S-wave velocities and resistivity is known to be practically independent of lithology. Since we try to interprete the velocity and the resistivity profile in combination and since we are rather interested in the general depth-dependent trend than in a detailed analyzis we assume that this simplification is still reasonable.

In isotropic saturated and dry rocks the dependence of P-and S-wave velocities on effective pressure is given by equations of the form (Shapiro, 2003)

$$V(P_{eff}) = A_V + K_V P_{eff} - B_V \exp\left(-DP_{eff}\right). \tag{1}$$

Here V can represent P- or S-wave velocity and denotes as a subscript that the physical meaning of the adjustable parameter (A, K, and B) actually depends on weather P- or S-wave velocity is considered. In contrast, in isotropic rocks parameter D should be the same for both wave modes. This parameter is a measure for the sensitivity of the rock properties to load induced crack closure and is given by

$$D = \frac{\theta_c}{K_{drys}} \tag{2}$$

Parameter θ_c was introduced by Shapiro (2003) as the piezosensitivity. K_{drys} is a reference matrix bulk modulus of a rock with no compliant and undeformed stiff porosity.

For isotropic porous rocks where mainly electrolytic charge transport occurs Kaselow and Shapiro (2004) have shown that the dependence of the logarithmic electrical formation factor F upon effective

Table 1: Best fit parameters with asymptotic standard errors for first optimization of P-wave, S-wave, and formation factor. In case of velocities A and B are in km/s, and in the case of formation factor they are dimensionless. Parameter D is given in 1/MPa.

Data	A	B	D
VP	5.906 ± 0.017	0.500 ± 0.035	0.060 ± 0.010
VS	3.494 ± 0.006	0.758 ± 0.029	0.111 ± 0.007
F	4.171 ± 0.020	1.147 ± 0.084	0.099 ± 0.012

pressure is also given by an equation of the form of eq. (1), namely:

$$\log F(P_{eff}) = A_F + K_F P_{eff} - B_F P_{eff} \exp\left(-DP_{eff}\right). \tag{3}$$

Again, parameter D is given by equation (2). Note that this derivation is valid for rocks where only electrolytic charge transport occurs.

From the analyzis of stress dependent velocity observations on numerous core samples from the KTB pilot hole we found that parameter K in equation 1 is usually $< 0.001 ms^{-1}Pa^{-1}$ and can thus be neglected. Parameter K reflects the influence of stiff porosity closure on the considered property. A negligible parameter K is in agreement with former interpretations that the KTB rocks show a very small or even no stiff porosity at all (Popp, 1994). Note in this case K_{drys} is equal to the bulk modulus of the grain material. Consequently, we simplify equation (1) and (3) to:

$$\Gamma(P_{eff}) = A_\Gamma - B_\Gamma \exp(-DP_{eff}), \tag{4}$$

where Γ stands for V_p, V_s, or F (in logarithmic scale). This equation is used for the further analyzis.

A further simplification is introduced by using isotropic depth-to-pressure transforms for confining and pore pressure, neglecting the anisotropy of confining stress at the KTB. Confining pressure P_c and pore pressure P_{fl} at a depth d are calculated using a constant rock (ρ_r) and pore fluid density (ρ_{fl}) of 2767 kg/m^3 and 1010 kg/m^3, respectively. The resulting depth-to-differential pressure transform reads

$$P_{diff} = P_c - P_{fl} = gd(\rho_r - \rho_{fl}). \tag{5}$$

It can be shown that the effective pressure P_{eff} for pore space deformation is just the differential pressure P_{diff} if the grain matrix material is homogenous and elastic (e.g., Zimmerman et al., 1986; Shapiro, 2003; Gurevich, 2004)), and/or the bulk porosity is low (Shapiro and Kaselow, 2003; Kaselow and Shapiro, 2004). Since the in-situ porosity of the metamorphic KTB rocks is below 1% (e.g., Kern et al., 1991) at least the last condition seems to be satisfied. Thus we assume that the effective pressure can be reasonably approximated with the differential pressure.

A simultaneous application of eq. (4) to the P-wave log, S-wave log and to the formation factor profile requires a two-step fit procedure which is described in detail by Kaselow (2004). In the first step the data sets are separately fitted using the non-linear least squares Marquardt-Levenberg algorithm with A, B, and D as adjustable parameters. Due to measurement errors, anisotropy and numerical artefacts of the iterative fit algorithm one cannot expect that parameter DP, DS, and DFF obtained from P-wave, S-wave, and formation factor fit, respectively, exactly coincide as theoretically predicted. Thus, the mean D of the three parameters is calculated and the fit procedure is repeated with D kept fixed. We assume that the parameters obtained from the second fit sufficiently approach the searched for values.

ANALYZIS AND RESULTS

We obtained for the first data fit the parameters given in Tab. (1). The rms of the residuals of P-, S-wave, and formation factor fit are 0.380, 0.210, and 0.695, respectively. The D parameters agree quite well, especially in the case of S-wave log and formation factor.

The repeated fit with D = mean(DP,DS,DFF) = (0.090 ± 0.009 1/MPa) revealed the final set of fit parameters given in Tab. (2). The rms of the residuals of P-, S-wave, and formation factor fit are 0.381, 0.210, and 0.695, respectively. Obviously, the parameters A and B change only slightly due to an averaging

Table 2: Best fit parameters with asymptotic standard errors for second optimization of P-wave, S-wave, and formation factor with D = 0.090 per MPa. Units are given in Tab. (1).

Data	A	B
VP	5.877 ± 0.009	0.547 ± 0.036
VS	3.507 ± 0.005	0.695 ± 0.020
FF	4.180 ± 0.016	1.106 ± 0.063

of parameter D. We conclude that the agreement between the D-values supports our hypothesis of the role of crack closure on the depth trend.

Figure (1) illustrate a comparison between the profiles and the best fit results. In addition the green diamonds represent P- and S-wave velocities calculated for the in-situ pressure from pressure dependent dry rock laboratory measurements. The saturated velocities were calculated from dry rock velocities using Gassmann's equations (Gassmann, 1951).

Although most of the laboratory velocities correspond to the sonic log velocities they are generally at the upper limit of the log velocities and remarkably higher between 55 and 65 MPa (2600–3500 m). This discrepancy between laboratory derived velocities and logging results in this specific depth range might be related to the heterogeneity and/or anisotropy of the KTB rocks. It is also known from further studies that the foliation dips from near vertical to horizontal orientation in this depth interval (Kern et al., 1991).

Generally, the enhanced seismic laboratory velocities might be caused by scattering and/or scaling effects. All cores investigated in the laboratory show no macroscopically visible crack. Thus we assume that the rock samples reflect the rock properties while the log velocities approach the in-situ formation velocities. This indicates that the crack size distribution of the intact rock and the formation differ due to larger fractures and faults within in the formation. Shapiro (2003) has shown that the piezosensitivity θ_c is approximately the inverse of the effective crack aspect ratio. If this is valid, a smaller crack aspect ratio should result in a higher θ_c.

A plot of the θ_c parameters obtained from the first fit results (θ_{cP} from DP and θ_{cS} from DS) of 42 samples of the KTB pilot hole and the corresponding values from the sonic logs is shown in Fig. (2). Obviously, θ_c obtained from the sonic logs is approx. 3.5 to 4.5 times larger than the mean θ_c obtained from the core samples. This indicates that the mean crack aspect ratio of the formation around the bore hole is 3.5 times smaller than the one of the laboratory samples. This might be understood as a hint for the influence of fractures and faults on the in-situ sonic velocities. Therefore, the in-situ stress sensitivity of the formation is higher that the one of the core samples. Moreover, Shapiro (2003) has shown that the stress sensitivity is directly related to non-linear elastic moduli through the coefficient β_k (see Zarembo and Krasilnikov, 1966, page 299-309), namely

$$K_{dry}(P_{eff}) = K_{dry}(0)\left[1 + \beta_k P_{eff}\right] \tag{6}$$

where the coefficient β_k is

$$\beta_k = \frac{\theta_c^2 \phi_{co}}{K_{dry}(0)}, \tag{7}$$

and ϕ_{c0} is the crack porosity at $P_{eff} = 0$. This means that also the elastic non-linearity of the KTB rocks is higher for the formation than for the core samples.

CONCLUSIONS

We have analyzed sonic P-wave, S-wave and deep lateral resistivity downhole loggings from the pilot hole of the German Continental Deep Drilling Site (KTB) using the isotropic piezosensitivity approach with respect to the general dependence of the logging results on increasing effective pressure with depth. We have neglected anisotropy and lithology. The latter influences P-wave velocities more than S-wave velocities and has only a very weak influence on resistivity. The used data set was completed with stress dependent velocity data obtained from core samples of the bore hole. We were able to fit pressure dependent sonic velocities and formation factor with equations of the form $\Gamma(P_{eff}) = A_\Gamma - B_\Gamma \exp(-DP_{eff})$. Best fits of the data revealed a parameter $D = 0.090 \pm 0.0091/MPa$ identical for all mentioned logging data.

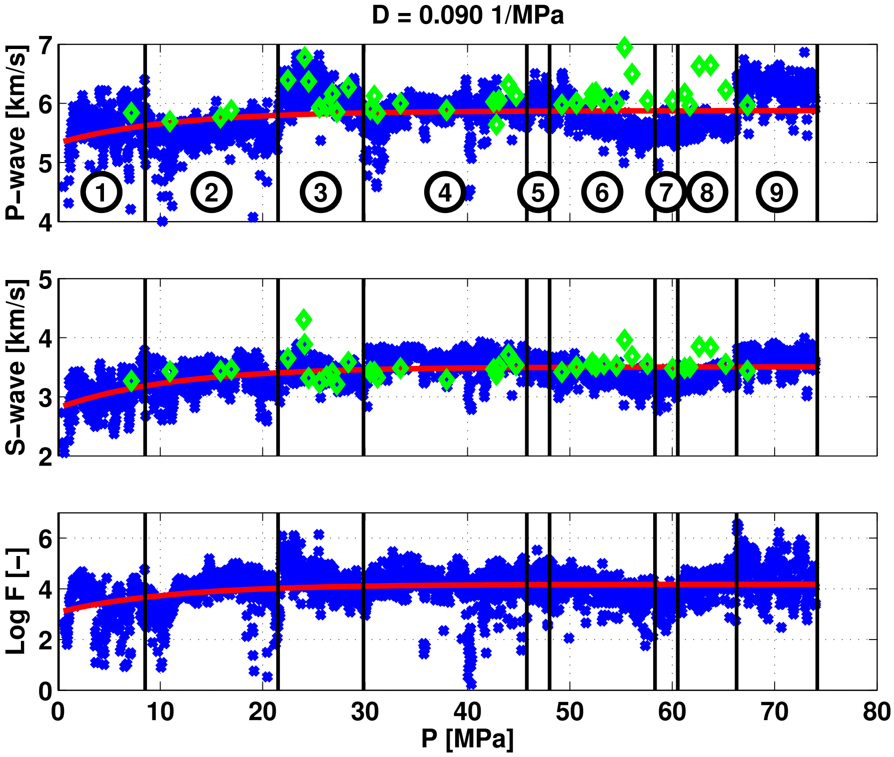

Figure 1: Logging (blue dots), laboratory derived in-situ velocities (green), and best fit (red line) for P-wave (top), S-wave (middle) and logarithmic formation factor. The best-fits were obtained for a common and fixed parameter D = 0.09 1/MPa, calculated as the average of the D parameters obtained from independent fits of the three downhole data sets.

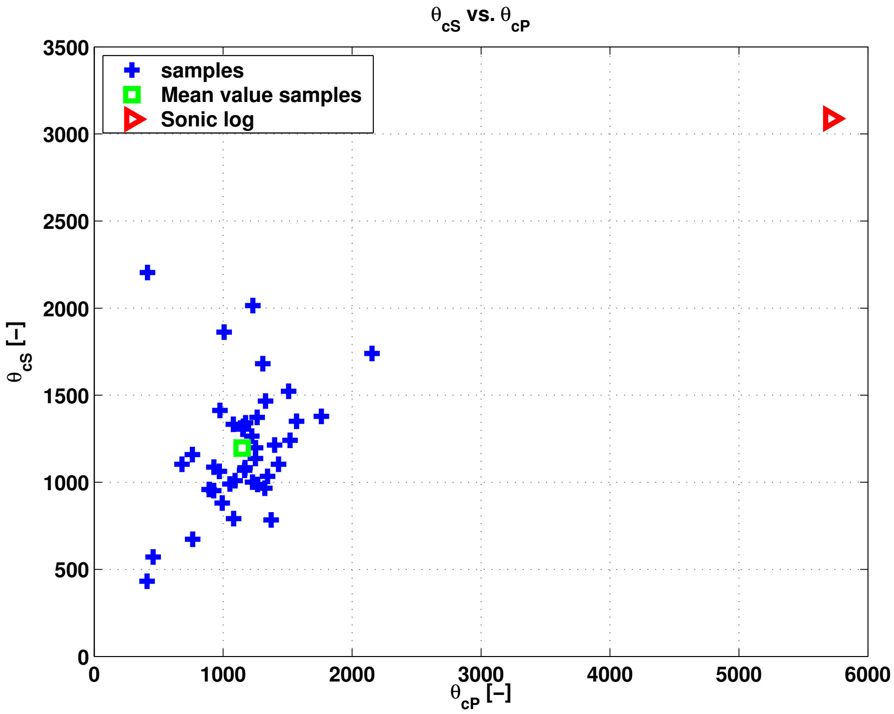

Figure 2: Cross-plot of θ_c obtained from first P-wave (θ_{cP}) and S-wave (θ_{cS}) fit from 42 core samples (blue) and sonic logging (red). Green square indicates mean θ_c from lab data.

This is in agreement with the theoretically derived universality of D for isotropic rocks. This universality of D supports our assumption that the general depth-dependence of P- and S-wave velocity and resistivity can be addressed to the closure of the compliant porosity. The dependence can be quantified in terms of the stress-sensitivity θ_c.

A comparison between the formation and the rock stress-sensitivity obtained from downhole measurements and laboratory observations, respectively, reveald 3.5 to 4.5 times higher stress-sensitivity of the formation rocks than of the apparently intact core samples, although the latter clearly show enhanced crack porosity due to pressure relaxation during and after recovery. We address this to a smaller effective crack aspect ratio of the formation in comparison to the one of the core samples. This difference might be due to larger fractures and faults which are absent in the macroscopically almost intact cores.

ACKNOWLEDGMENTS

This work was kindly supported by German Science Foundation (DFG) gant SH55/5-1 and the sponsors of the *Wave Inversion Technology (WIT) Consortium*, Karlsruhe, Germany.

REFERENCES

Duba, A., Heikamp, S., Meurer, W., Nover, G., and Will, G. (1994). Evidence from borehole samples for the role of accessory minerals in lower-crustal conductivity. *Nature*, 367:59–61.

ELEKTB-Group (1997). KTB and the electrical conductivity of the crust.

Emmermann, R. and Lauterjung, J. (1997). The German Continental Deep Drilling Program KTB. 102(B8):18179–18201.

Emmermann, R. and Rieschmüller, H. (1990). Das Kontinentale Tiefbohrprogramm der Bundesrepublik Deutschland (KTB) - Aktueller Stand der Planung der Hauptbohrung. *Die Geowissenschaften*, 9:241–257.

Gassmann, F. (1951). Über die Elastizität poröser Medien. *Vierteljahresschrift der Naturforschenden Gesellschaft in Zürich*, 96:1–23.

Gurevich, B. (2004). A simple derivation of the effective stress coefficient for seismic velocities in porous rocks. *Geophysics*, 69(2):393–397.

Haak, V. and Jones, A. G., editors (1997). *The KTB deep drill hole.*, volume 102, chapter Special section. AGU.

Huenges, E., Buntebarth, G., Kern, H., Nover, G., and Rauen, A. (1990). Petrophysikalische Untersuchungen an Bohrkernen unter simulierten in-situ Bedingungen. eine brücke zwischen Feldlabor und Bohrlochmessungen. Ktb rep. 90–4, Niedersächsisches Landesamt für Bodenforschung, Hannover, Germany.

Kaselow, A. (2004). *The Stress-Sensitivity-Approach: Theory and Application.* PhD thesis, Freie Universität Berlin, Berlin, Germany. http://jorge.ub.fu-berlin.de/work/DissSearch.

Kaselow, A. and Shapiro, S. (2004). Stress sensitivity of elastic moduli and electrical resistivity in porous rocks. *J. Geophys. Eng.*, 1(1):1–11.

Kern, H., Popp, T., and Schmidt, R. (1994). The effect of deviatoric stress on the rock properties: an experimental study simulating the in-situ stress field at the KTB drilling site, Germany. *Surv. Geophys.*, 15:467–479.

Kern, H. and Schmidt, R. (1990). Physical properties of the KTB core samples at simulated in situ conditions. *Scientific Drilling*, 1:217–223.

Kern, H., Schmidt, R., and Popp, T. (1991). The velocity and density structure of the 4000 m crustal segment of the KTB drilling site and their relation to lithological and microstructural characteristics of the rock: an experimantal approach. *Sci. Drill.*, 2:130–145.

Nover, G., Heikamp, S., Kontny, A., and Duba, A. (1995). The effect of pressure on the electrical conductivity of KTB rocks. *Surveys in Geophysics*, pages 63–81.

Nover, G. and Will, G. (1991). Laboratory measurements on KTB core samples: complex resistivity, zeta potential, permeability, and density as a tool for the detection of flow phenomena. *Scientific Drilling*, 2:90–100.

Popp, T. (1994). *Der Einfluss von Gesteinsmarix, Mikrorissgefüge und intergranularen Fluiden auf die elastischen Wellengeschwindigkeiten und die elektrische Leitfähigkeit krustenrelevanter Gesteine unter PT-Bedingungen.* PhD thesis, Kiel University, Kiel.

Rauen, A. (1991). *Untersuchungen des komplexen elektrischen Widerstandes, insbesondere dessen Anisotropie und Frequenzabhängigkeit, vonProben des Kontinentalen Tiefbohrprogramm der Bundesrepublik Deutschland (KTB).* PhD thesis, Fak. für Geowiss., Univ. München, München, Germany.

Rauen, A., Duyster, J., Heikamp, S., Kontny, A., Nover, G., and Röckel, T. (1994). Electrical conductivity of a KTB core from 7000 m: Effects of cracks and ore minerals. *Scientific Drilling*, 4:197–206.

Shapiro, S. A. (2003). Piezosensitivity of porous and fractured rocks. *Geophysics*, 68(2):482–486.

Shapiro, S. A. and Kaselow, A. (2003). Porosity and elastic anisotropy of rocks under tectonic stresses and pore pressure changes. *submitted to Geophysics.*

Zarembo, L. K. and Krasilnikov, V. A. (1966). Introduction to non-linear acoustics. *Nauka, Glavnaja Redaktsija Phys.-Math. Lit. (in Russsian).*

Zimmerman, R. W., Somerton, W., and King, M. (1986). Compressibility of porous rocks. 91:12765–12777.