

Observations of fluid induced deformation of the upper crust of the Earth: Investigations about the large scale injection experiment at the KTB site / Germany

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Abstract

A tiltmeter array, consisting of five high resolution borehole tiltmeters of the ASKANIA type, was installed in the surrounding area of the KTB location in mid 2003 (KTB: Continental deep drilling site in Germany). There, an injection experiment of water started in June, 2004. The injection had a medium rate of about 200 liters/minute into the KTB pilot borehole (4000 meters deep). The aim of the research project is to observe and interpret the deformation of the upper crust at kilometre scale. We observe elastic as well as non-elastic responses: Changes of the rheologic properties due to pore pressure increase cause changes in the tidal parameters of M2 and O1. However, these changes are only observed for the north-south direction, which confirms seismological results: The induced seismicity, due to the injection, takes place more northwards of KTB than east- or westwards. Further we expect sudden changes of the drift curve as well as slow variations. For the separation of the induced drift signal it is necessary to eliminate locally induced interference, e.g. arising from groundwater variations or barometric pressure effects. The pore pressure changes observed at all stations show significant correlations with the recorded tilt signals. Taking into account these environmental influences and eliminating them we have now the potential to separate the injection induced deformation signal: During the injection period of about one year the tilt signals of three stations show a significant additional drift oriented from the stations in direction of the KTB site. In the next step these observations will be interpreted by numerical modelling, using a high resolution finite-element-model.

Keywords: KTB injection, fluid dynamics, deformation of the upper crust, tiltmeter observations, geodynamics

1 Introduction

In connection with the development of swarm earthquakes and related stress and strain processes the influence of fluids is more and more discussed. Beside different observations showing the correlation of fluid activities and the occurrence of swarm earthquakes numerical modelling yields some significant hints that the regional stress field alone cannot cause the local stress accumulation in the middle crust of the Earth (Yamashita, 1999; Kurz et al., 2003, 2004). However, the consideration of pore pressure variations in connection with geological features like fault zones and the brittle ductile transient zone in the middle crust results in high local stress accumulations in the crust, which are necessary for the appearance of swarm earthquakes. Up to now the whole process is not completely understood and related large scale experiments were not realized until 2003.

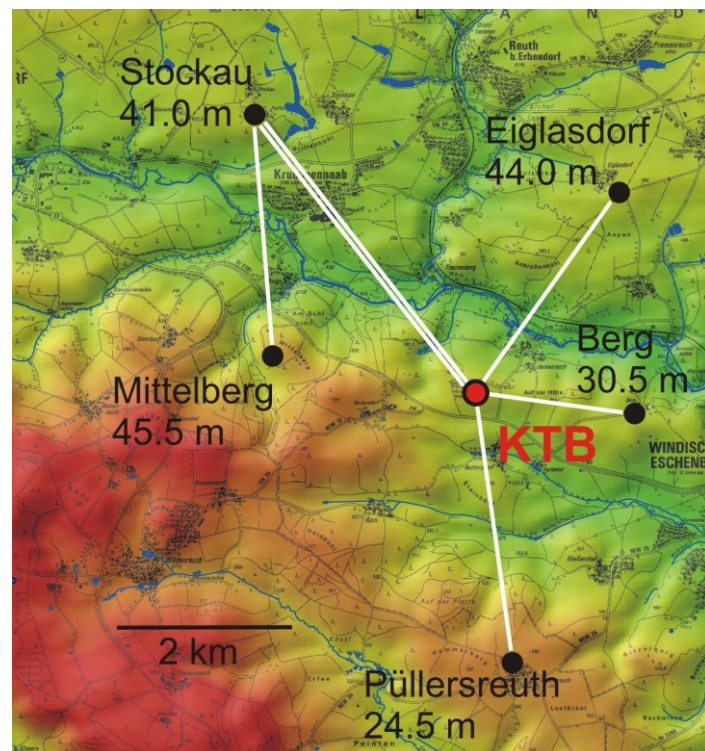
This research project combines a large scale injection experiment with the monitoring of induced seismicity and deformation. The interpretation of the process will be carried out by a high resolution three dimensional numerical modelling, using the finite-element-method. This interpretation can help to improve the knowledge about the interaction of fluid dynamics, stress accumulation, induced deformation and seismic activities, regarding swarm earthquakes.

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2 Tiltmeter-array around KTB

In June, 2004, at the German deep drilling site KTB, a water injection experiment started in the pilot borehole (4000 meters deep), to be completed in May 2005. The injection had a medium rate of 200 liters/minute into the pilot hole. Beside monitoring of induced seismicity by a local network, a tiltmeter array was installed in the surrounding area of the KTB location in mid 2003 (Fig. 1), consisting of five high resolution borehole tiltmeters of the ASKANIA type (Weise et al., 1999). The aim of the research project was to observe the induced deformation of the upper crust at kilometer scale (Jahr et al., 2005). Numerical modelling revealed that pressure built up by the given injection rate would cause a deformation of about 30 nrad within 4 months at the selected stations.

Fig. 1. The area around the KTB-site: The five tiltmeter stations were connected via WLAN to transmit the data on-line. Now the remaining stations Mittelberg, Püllersreuth, Berg and Eiglasdorf are running offline.



The locations of the tiltmeter stations in the vicinity of KTB are at distances of 1.6 to 3.2 km. The instruments are installed in bedrock in depths between 24.5 and 45.5 m depending on the depth of the sediment cover, usually less than 20 m. The tiltmeters are equipped with a 3-D geophone set in order to complete the local seismic network. Next to each tiltmeter borehole in an additional drill hole the groundwater level is monitored as pore pressure variation. Tilt, groundwater level and seismic data were downloaded via a wireless LAN to KTB and further via Internet to the GFZ-Potsdam and the Institute of Geosciences, Jena. The project was carried out in close cooperation with seismologists of the GFZ-Potsdam who operated the seismic network and the WLAN. The wireless connections are given in Fig. 1 as well. Thus, the quality of the raw tiltmeter data and the remotely performed instrument calibration could be checked every day. We also installed a meteorological station at KTB to monitor barometric pressure and precipitation.

2 Observed data

Fig. 2 shows the obtained data until the end of the year 2005. Due to technical problems and the end of funding we had to terminate the recordings at Stockkau in August 2005 and the recording systems had to be replaced by systems without WLAN. The tilt data consist of long and uninterrupted sections. The comparison of the tidal amplitudes in the self-scaled plots reveals the different long-term drifts at each station: big tides denote small drifts.

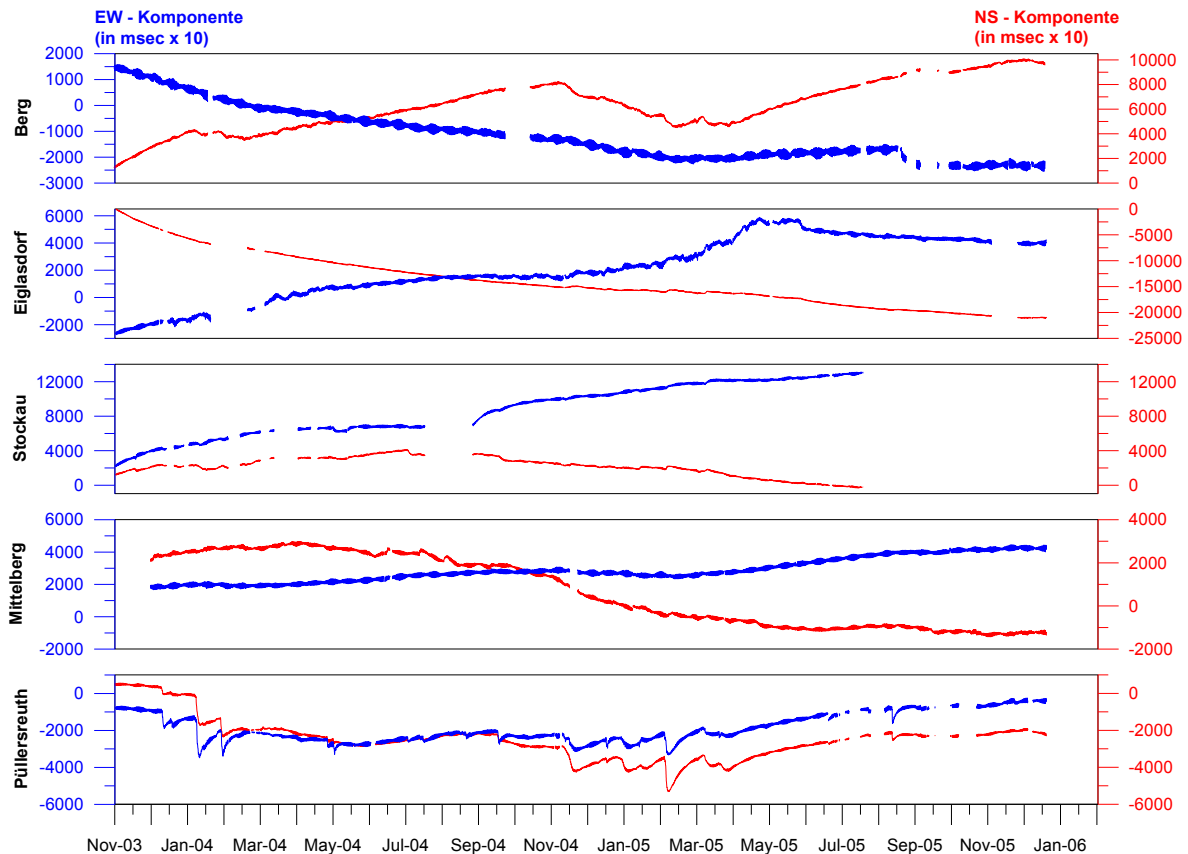


Fig. 2. Tidal recordings: After pre-processing the time series of the tiltmeter observations the drift behaviour can be visualised. The data is displayed in milliseconds of arc times 10 corresponding to about 100 nrad for the maximum tidal amplitudes. Mittelberg shows the lowest drift rates, while in Püllersreuth non-linear effects were caused by heavy precipitation. Data gaps at Eiglasdorf and Berg were caused by malfunctioning data loggers. In Stockkau the tiltmeter failed in July 2005.

There are also different reactions to precipitation and local ground water changes. Heavy rainfall usually results in strong deviations with a relaxation of several days. The injection induced variations of tidal parameters, additional drifts of the records (in the order of the tidal amplitudes) and a characteristic movement of the tip of the tiltmeter pendulum (hodogram). The correction of the data for local meteorological effects (precipitation, air pressure) and ground water is in progress.

3 Results and discussion

Although the obtained tidal parameters show a wide scatter, the variations at the individual stations correlate, either no variation or slight variations, respectively. Fig. 3 gives the results for the main tidal constituents M2 (semi-diurnal) and O1 (diurnal): There is a slight change in the parameters corresponding with the injection, here shown for the constituents M2 and O1: Three different periods can be distinguished, before, during and after the injection. The

analyses show a slight increase of the parameters in the component North-South rather than in East-West. This corresponds to the findings regarding the seismicity which increased north of the KTB site. This can be interpreted as an injection induced change of the elasticity of the rock. This result is confirmed by the separated long-term drift. Although these drifts are still preliminary because local effects still have to be analysed and corrected, we can see common trends. Especially these drifts towards the injection center show a surface deformation correlating with the injection induced uplift of the KTB-site. Further, the hodograms reveal drift directions corresponding to geological strikes.

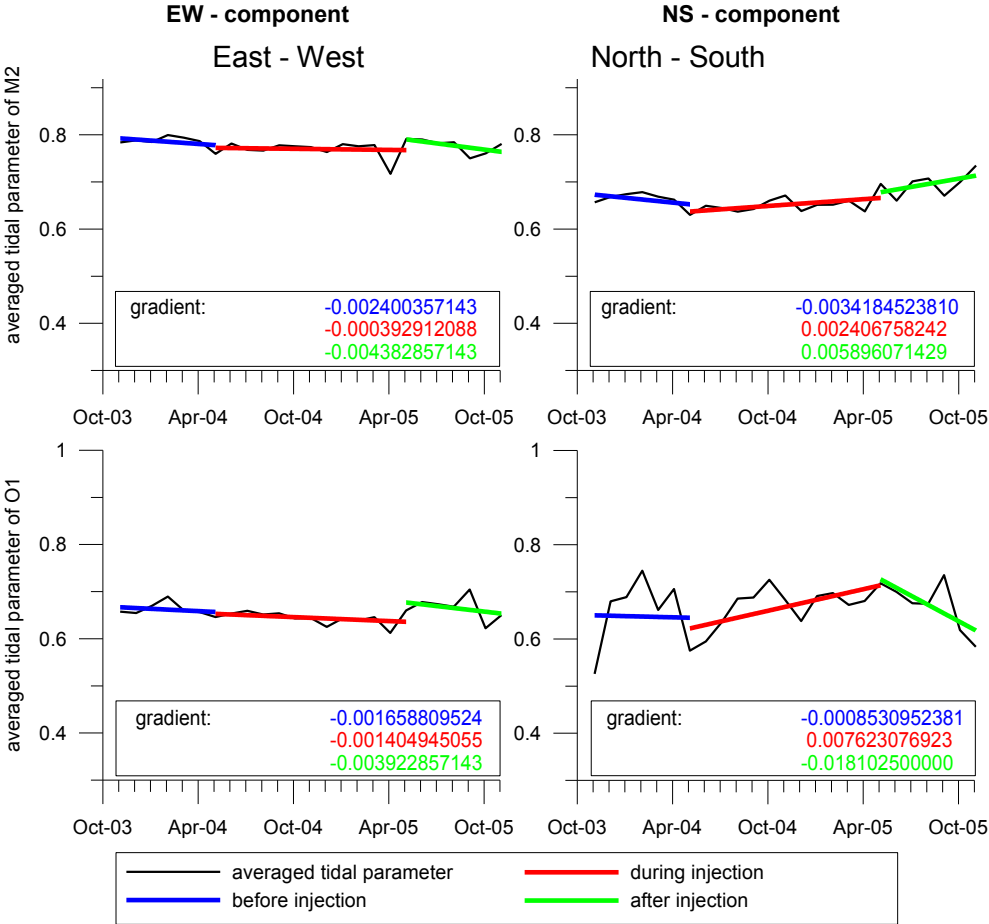


Fig. 3. Variation of tidal parameters of the main tidal constituents M2 and O1: Three different periods can be distinguished, before, during and after the injection. The effect is stronger in North-South than in East-West.

Conclusion

We can summarise that we found three different injection induced effects: Variations of tidal parameters, long-term drifts, and direct elastic tilts. These signals now need numerical interpretation.

The injection tests at KTB were accompanied by induced seismicity (Shapiro et al., 2006). Here, we have a combination of surface deformation and seismicity which was already discussed by Jentzsch et al. (2001). The interpretation with regard to physical properties of the rock and concerning fluid induced processes (Fujimori et al., 2001) will be

done by numerical modelling. We already modelled the expected deformation applying POEL (by R.J. Wang), but for a detailed modelling of the geologic structure we will use the Finite-Element-software ABAQUS. The first model is already under construction (Jahr et al., 2006).

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