Jerks and long-term variations in borehole temperatures in the Transcaucasus and near the Kopet-Dagh Front Fault in Turkmenistan

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Abstract

Microtemperature variations are reported which were recorded in the Transcaucasus and in Turkmenistan during 1992 until 1994. The variations are understood as precursory phenomena of earthquake in these regions. It is demonstrated that jerks, excursions and steps occur whose amplitude and/or width of its half value relate to the tectonic activity, i.e. in this case to the subsequent magnitude and distance of the earthquake.

The temperature itself is, in general, less informative than its gradient, because the amplitude of the variations is strongly dependent on the petrophysical properties of the layer at which the temperature is recorded.

From the analysed data it can be estimated that the variations of gradient are several tens of mK/km and that they occur a few days before the onset of earthquakes of M approx. 4-5 and a few weeks before strong earthquakes.

Introduction

Temperature variations in the uppermost crustal layers result from several external as well as internal effects. These variations superpose the basic and rather stable energy flow from the earth's interior, which is about 40 to 60 mW/m^2 at the surface.

Variations of the surface temperature, caused by diurnal, annual or long-term waves, jerks or other changes, dissipate into the subground to different extents and may be detected by measurements in the subground. Also environmental conditions, e.g. the cutting of tropical forest in medieval times, cause a variation of the subsurface temperature as Cermak (1971) has demonstrated with measurements.

Variations of the nearly stationary heat flow through the mantle and the lower crust, may be barely detectable by measurements over a few years. Nevertheless, local or regional variations in temperature occur. These are due to geodynamical effects. The tides of the solid earth and variations of the tectonical stress can cause, or result in, a differential mass motion between the rock matrix and the pore fluid under specific structural conditions, and these relative motions of the pore fluid with respect to the rock matrix yield a temperature variation at a thermometer which is fixed on the casing of a borehole. This water movement is relatively small and barely exceeds a few centimeters in its vertical component, which means that the expected temperature variations reach amplitudes of milli-Kelvin. Shimamura (1980, 1983) and Shimamura et al. (1985) were the

first to have intensively studied temperature variations in boreholes. Somewhat later, such measurements were also performed by van Ruymbeke et al. (1991), in order to analyse ground water movements.

After long-term stationary measurements in Georgia and in Turkmenistan, i.e. in areas of strong tectonical activity, some results can be reported regarding the frequency spectrum and temperature variations in small spatial domains.

Method

The temperatures were measured at depths which are deep enough not be influenced by annual varations at the surface. An annual sine wave of an amplitude of 10 degrees decreases down to less than 0.5 mK at a depth of 80 m (e.g. Buntebarth, 1984), the lowest depth at which the temperature was recorded. This value is calculated and may be superposed by strong rain or by other reasons resulting in a movement of water.

The resolution of the thermometers which are used is approximately a quarter of one milli-Kelvin. The quartz sensors used are very stable in time and do not exceed the resolution within one year. Therefore, they are applicable for long-term registration. The sensor electronics comprises the oscillator, a frequency divider and a chopper for 2-wire-connection. The transduced frequency is measured at the surface with high accuracy of 10-5Hz and stored on computer. As well as the temperature, the water level is also recorded in a few boreholes using mechanical equipment.

In order to have proof of the tectonical activity, the seismicity and larger earthquakes of each region are analysed contemporaneously with the temperature records. Because the surface variations of the temperature diminishes with depth and the sensors are placed not above 80 m, the surface effects are minimized. If water flow occurs, it is assumed to result from deformations of the crust which force the water to flow opposite to the pressure gradient resulting in a temperature variation.

A quantitative estimation of deformation applies an empirical relationship between the magnitude of an earthquake and distance from the epicentre. Based on many data Dobrovolsky (1991) suggests the formulas:

$$M < 5 \qquad \varepsilon = \left(\frac{10^{0.5M} - 3.06}{R} \right)^3 \tag{1}$$

$$M \geq 5 \qquad \varepsilon = \left(\frac{10^{0.433M} - 2.73}{R} \right)^3 \tag{2}$$

These relations average the physical properties which are implicitly involved, so that the constants can deviate in individual cases. The deformation * is also related to the shape of the pores and grains, to the cementation of the pore space, to the pore filling, the permeability and other factors. More simply, the deformation depends on the lithology. Shimamura (1983) confirmed the relationship between the temperature of the shallow depth and the deformation which results from earthquakes. He concludes that temperature steps in a borehole correlate with the distance from the epicentre and with the magnitude of the earthquake.

Results

Three large earthquakes occurred in the Great Caucasus during the period of observation in 1991 and 1992 (fig. 1). The distance of the boreholes at which the thermometers were installed from the epicenters was more than 100 km but less than 200 km. Table 1 shows the events and variations in temperature.

The temperature does not vary at all depths within a borehole. Fig. 2b demonstrates that the lower thermometer exhibits a constant temperature during the second half of 1991, but some variations are recorded at the upper depth of 80 m. At that depth, the borehole crosses an aquifer which seems more sensitive to stress changes than the layers at a greater depth. The borehole is open down to 240 m. This observation encourages one to plot the mean tempearture gradient between both sensors instead of each temperature. The result of the first half of 1991 is shown in fig. 2a. Even the records are not continuous, the figure demonstrates that the temperature gradient is more sensitive to variations than the temperature itself.
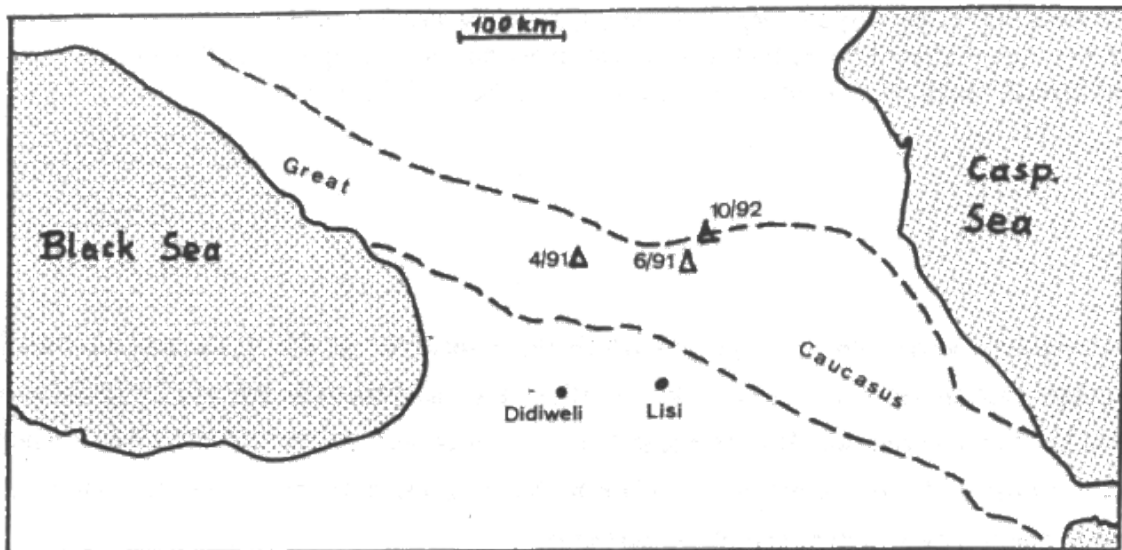

Fig. 1: *Stations for temperature measurements and epicentres of the largest earthquakes during 1991 and 1992 in Georgia*

Table 1: *Major earthquakes 1991 and 1992 in the Transcaucasus and the distance from the boreholes Didiweli and Lisi.*

Date	Magnitude	Distance from and deformation at				Temperature variation	
		Didiweli		Lisi		amplitude	time before the event
		x (km)	10^{12} epsilon	x (km)	10^{12} epsilon	(mK)	(days)
04/91	6.9	112	461			12	30
04/91	6.9			146	293	1	*
06/91	6.2			117	70	0.3	(0 or 46)
07/91	5.0			109	2	0.3	(19)
10/91	4.9			163	0.5		**
10/92	5.3			87	11	3	56

* data are not continuous
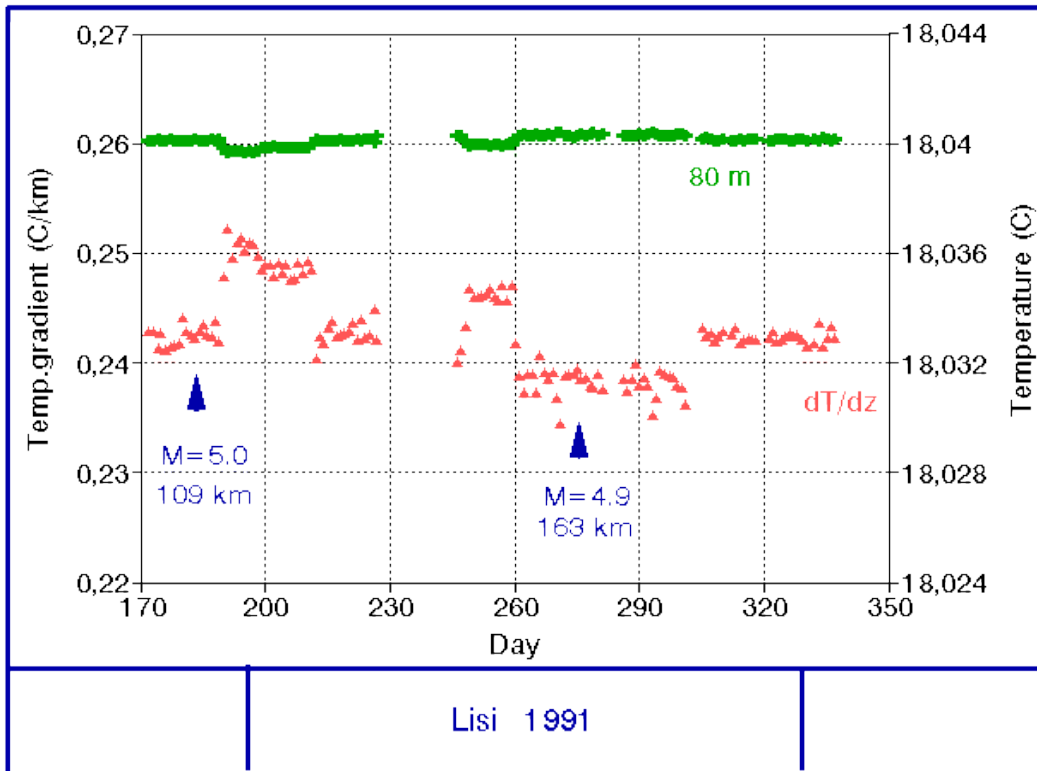** large variation
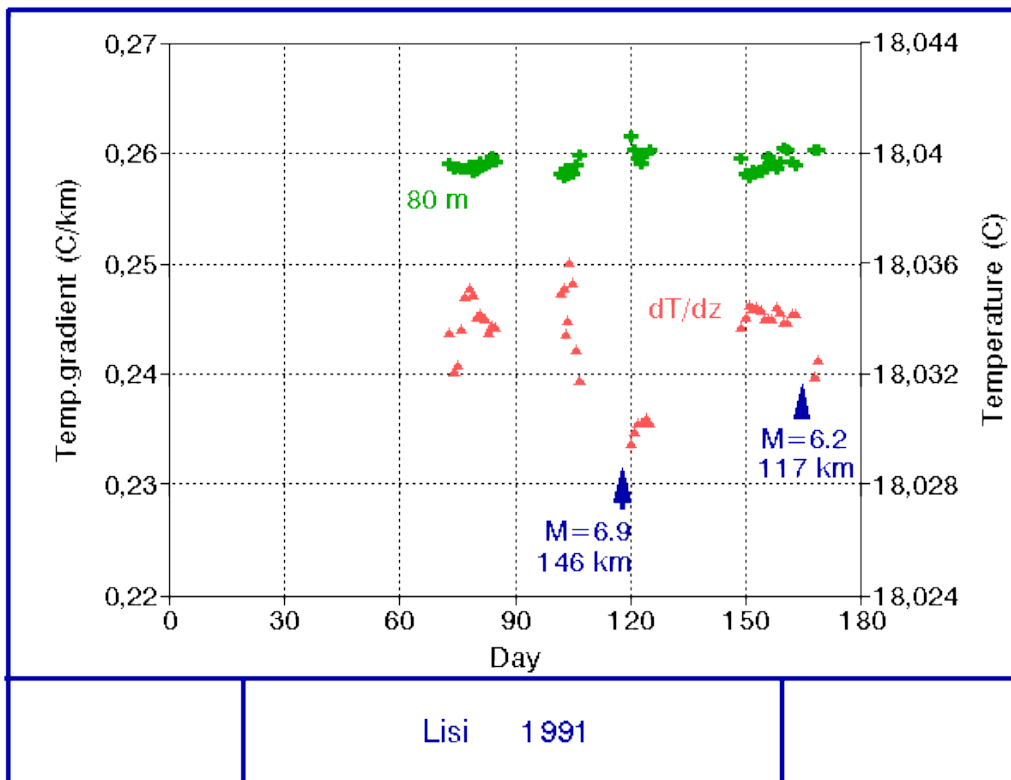
Fig. 2: *Temperature records at Lisi/Georgia with significant earthquakes during 1991*
a) first half of the year with temperature gradient
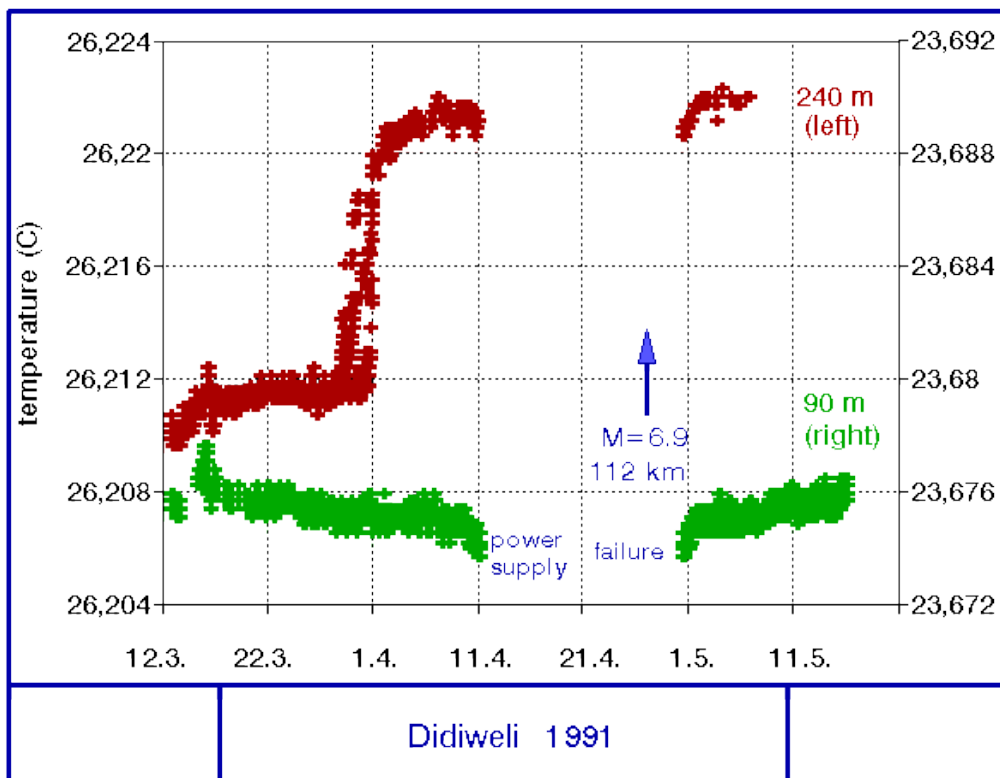*b) second half of the year, upper and lower temperatures*

Fig. 3: *Temperature records at Didiweli/Georgia at depth of 90 and 240 m during Spring 1991 and the occurrence of the earthquake*

If tectonical stress accumulates somewhere, water of an aquifer is forced to migrate to low pressure regions. This advective fluid flow can be monitored in distances between 100 and 200 km, according to the experience. It yields a measured temperature variation of up to 3 mK at the borehole Lisi. Some relationship may exist between the temperature amplitude and the stress variation. Because the stress field is unknown, the stress release during an earthquake might roughly relate to it. The distance between the centre of stress accumulation, which yields the centre of an earthquake, and the thermometer is taken into account when applying the deformation which is reported by Dobrovolsky (1991).

At another borehole (Didiweli) at which the temperature was recorded over a short period only, a remarkable piece of information was obtained. The largest earthquake which occurred during the last years in the Caucasus, occurred during the period of recording. Its epicenter was nearer to Didiweli than to Lisi, so that the preparation of the earthquake could be studied in more detail.

The temperature of the artesian well Didiweli was recorded at depths of 90 and 240 m (Fig. 3). After a constant temperature during March 1991, it increased by 12 mK within 3 days at the lower sensor and was constant again after the rise. After the onset of the increase until the occurrence of the earthquake, 30 days passed. The step in the temperature could not be seen at the upper sensor. The variation in the temperature can be explained simply. The volume of warmer water which passed the lower sensor was much less than the volume which entered the borehole at a depth between both sensors, because the rise in temperature at the upper sensor did not exceed the resolution. Therefore, the supply of water derives mainly from a depth between 90 und 240 m. This is a further example of the need to record the borehole temperature at several depths.

In Turkmenistan, the temperature was measured at 2 sites (Berzengi and Manysh) with high resolution. Their location is shown in fig. 4. The water level was also recorded in several boreholes of different depths, at various distances not exceeding 2 km.

From 1992 to 1994, some variations in the temperature of the Berzengi borehole were recorded (fig.5 and fig.6). The borehole is 2000 m deep, and the temperature is measured at depths of 90 m and 140 m. During 1992, one strong jerk was recorded (Tab. 2) which occurred on the second day after a shallow and close earthquake which focal depth was determined at 3 km (100 % uncertainty). It seems that a ground-water flow was induced after the stress release, which caused the recorded temperature excursion of 5 days at the upper
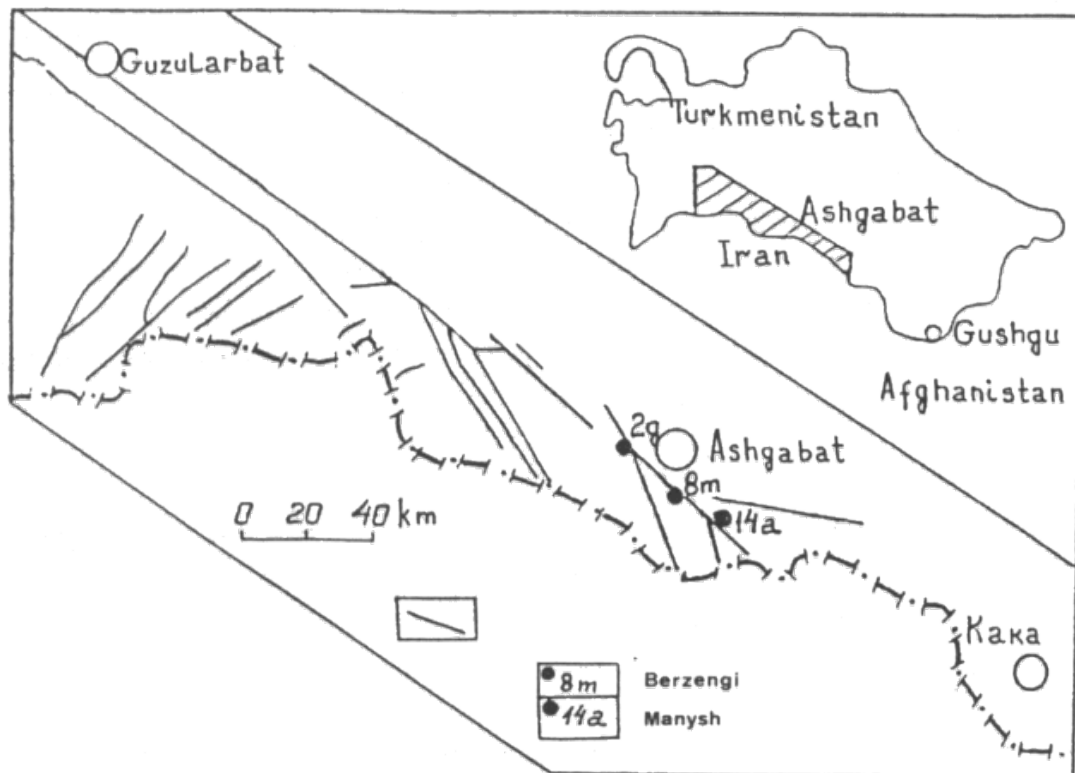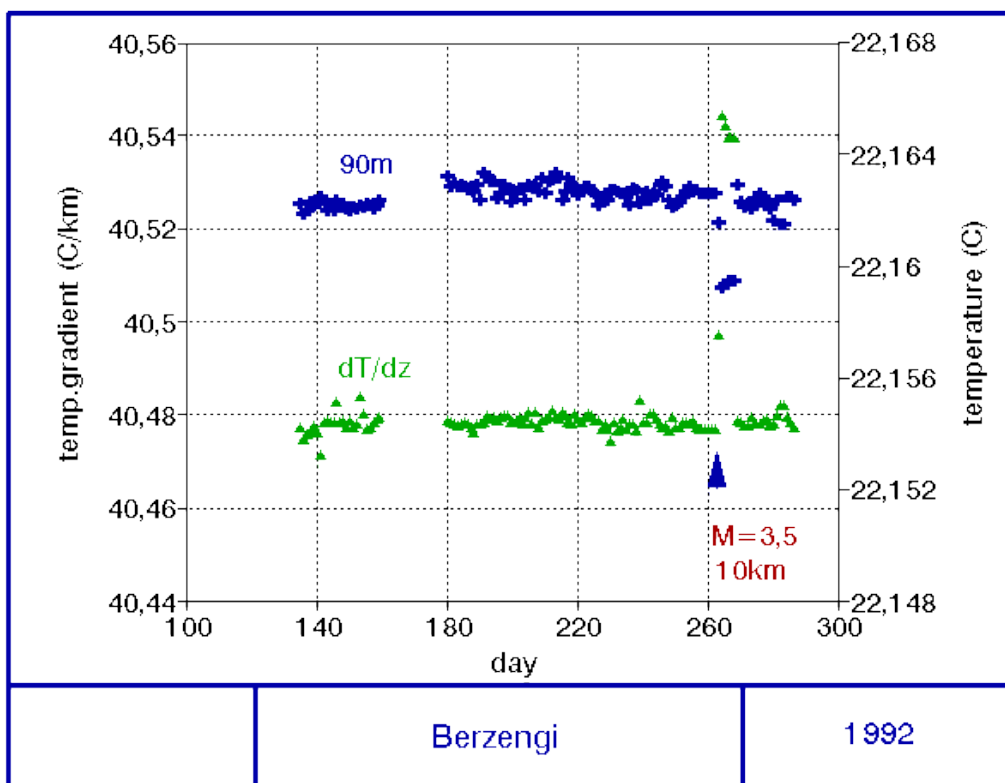
Fig. 4: *Location of boreholes for temperature and water level measurements near the Kopet Dagh front fault in Turkmenistan*
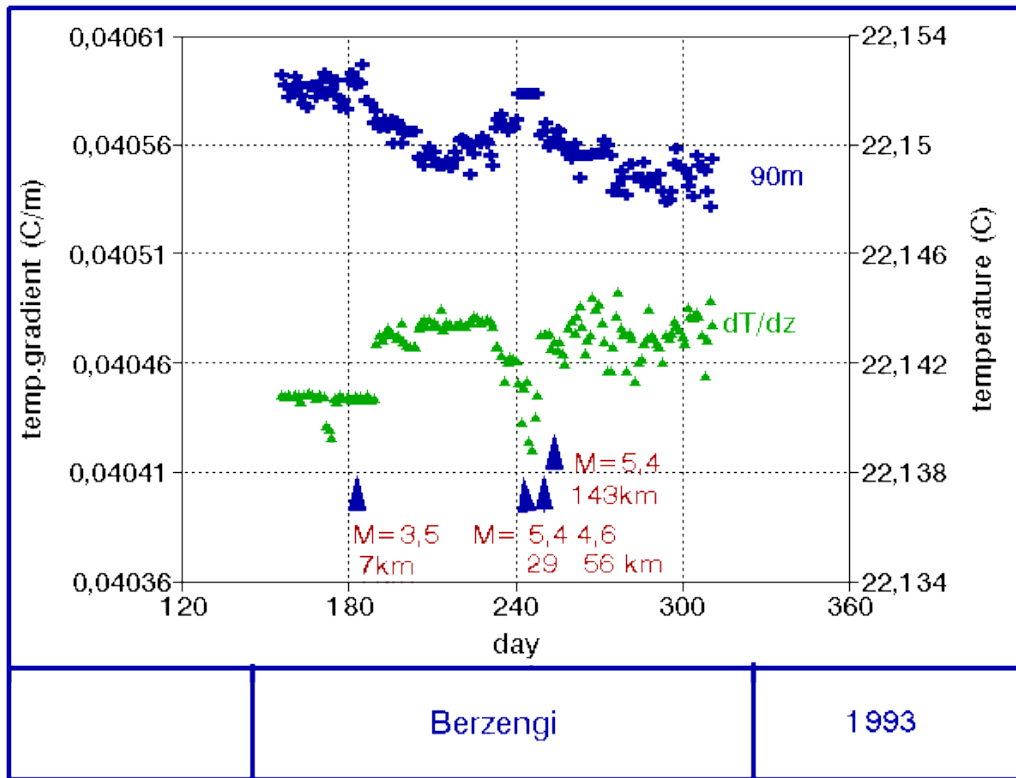
Fig. 5: *Temperature records at 90 m and the mean gradient (90 to 140 m) at Berzengi/ Turkmenistan during a) 1992 and b) 1993 with the onset of earthquakes*
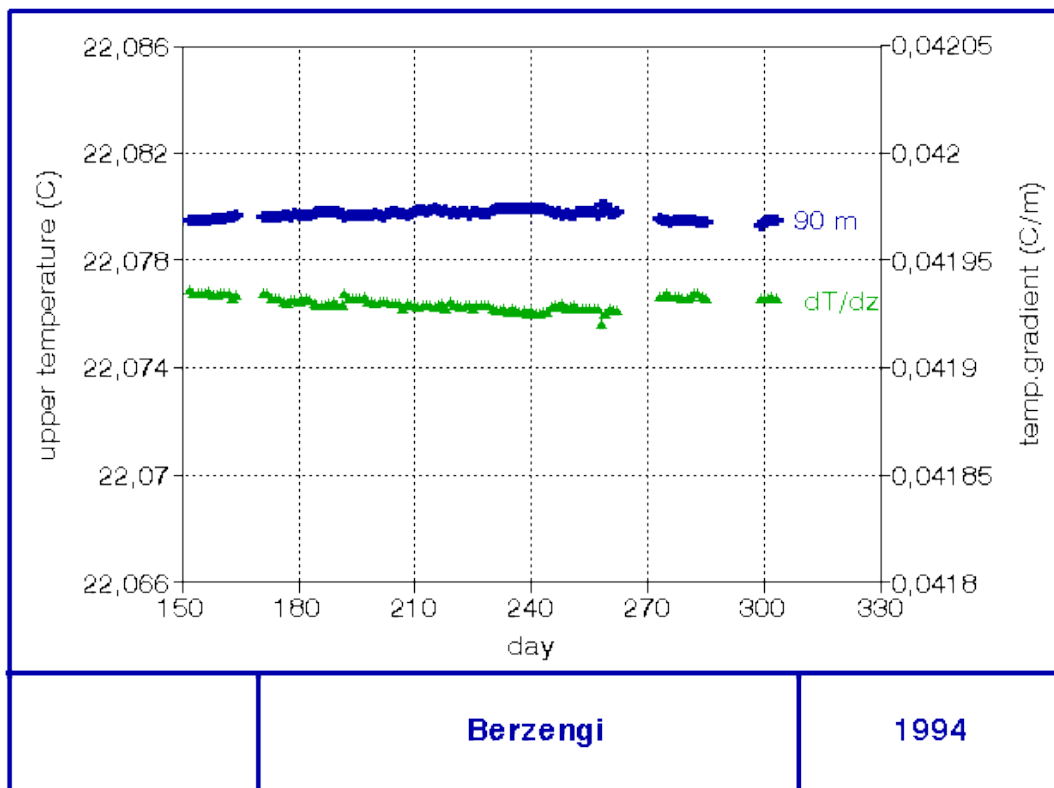

Fig. 6: *Temperature records at 90 m and the mean gradient (90 to 140 m) at Berzengi/ Turkmenistan during 1994*

sensor only. During 1993, three temperature events were recorded (Fig. 5b), i.e. two excursions and one step. After the last event, a high variation with constant mean value was recorded until the operation ended in 1993 because of a power supply failure. After starting up again in May 1994, no thermal event was recorded at this station throughout the year.

The station Manysh, which is an artesian well, was installed in 1993. The water discharge is approx. 3 l/min and is located 19 km SE of the Berzengi station (Fig. 4). During the first year of operation, the temperature at the lower sensor (z=130 m) varied with a higher amplitude than the upper one at a depth of 80 m. As a consequence of the preparation of the earthquake swarm in September 1993, the temperature gradient decreased and reached a minimum during the seismic activity (fig. 7a). When it stopped the temperature gradient gradually increased again (Tab.2). Due to energy problems, registration was interrupted until Autumn 1994. Two thermal events are recorded in November and December (fig.7b). The first one is related to a very close seismic event with a magnitude of approx. 3. The minimum of the temperature gradient, which must be estimated, occurred no more than two days before the event. The second excursion of the temperature gradient exhibits an extremum of 19 mK/km and occurred one day before a nearby and shallow earthquake with an magnitude of more than 3.5.
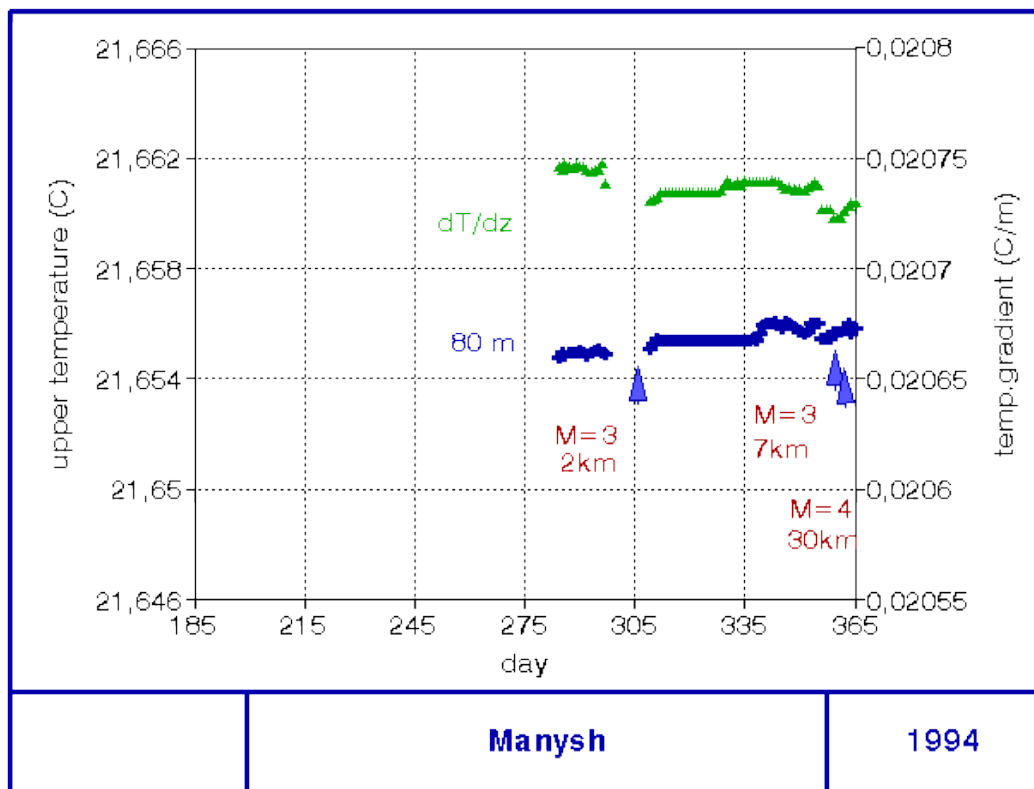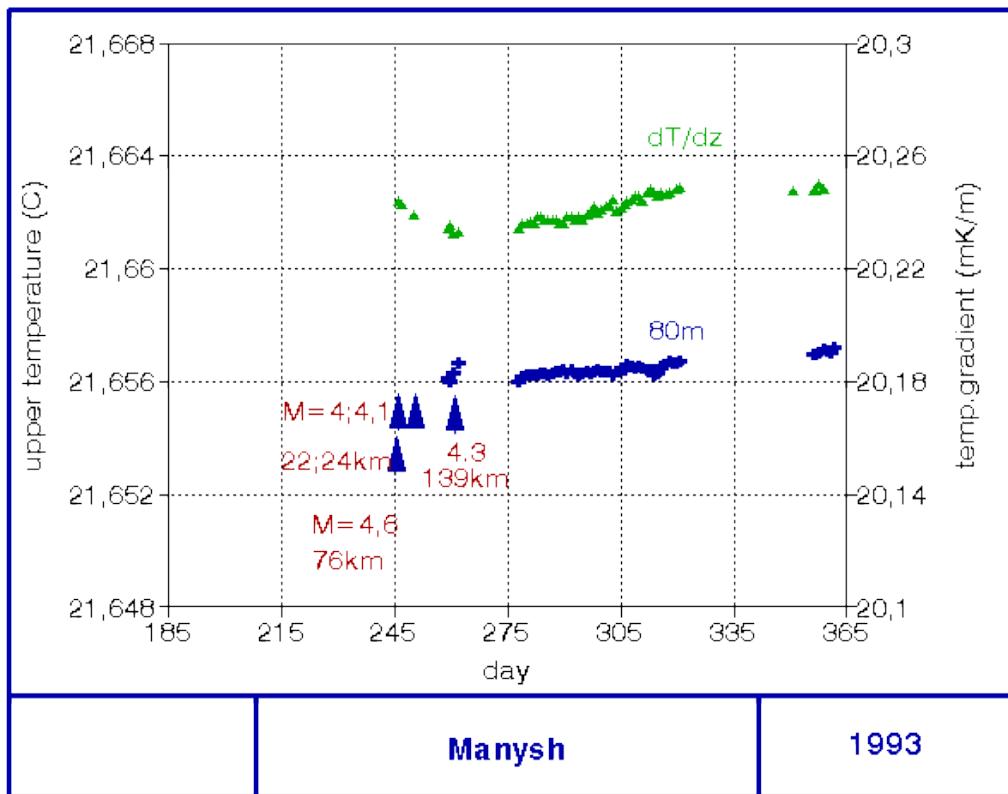
Fig. 7: *Temperature records at 80 m of depth in Manysh (no.14a) and its gradient between 80 and 130 m and the onset of earthquakes a) 1993 and b) 1994*

Table 2: *Seismic activity 1992 until 1994 near Ashgabat/Turkmenistan and the temperature variation in boreholes*

| Date | Magnitude | Distance from and deformation at | | | | Temperature variation | | | Width of half value |
| | | Didiweli | | Lisi | | amplitude | grad T | time before the event | |
		x (km)	10^{12} epsilon	x (km)	10^{12} epsilon	(mK/km)	(mK)	(days)	(days)
09/92	~ 3.5	10	150			4	66	2	~ 3
07/93	~ 3.5	7	438				15	3	~ 2
08/93	~ 5.4	29	408			1	24	27	step
7. Sept. 93	4.6	56	43					4	1
10. Sept. 93	5.4	143	3			3	60	7	
3. Sept. 93	4.0 4.1	143		22 24		86 94		0*	36
7. Sept. 93	4.6			76	17	2*	17	4*	
19. Sept. 93	4.3			139	1				
11/94	~ 3			2		1	19	< 2	7
12/94	~ 3 4.0			30		1	15	1	7

* extrapolated

A few hours later, a stronger earthquake (M=4.5) occurred approx. 30 km away. The temperature of the outflowing water of this artesian well, which encounters Paleocene sedimentary rocks at a depth of 340 m, ranges from 19 °C to 21 °C depending on the season. No jump or excursion of the temperature can be seen from the sinusoidal annual curve. The salt content of the discharged water does not exceed the uncertainty of 5 %. However, it can be assumed that it is 5 % lower at the lower temperature during winter time. The flow rate is controlled every 5 days. It decreased from the beginning of 1994 within 2 months from 60 ml/s to 55 ml/s and reached 53 ml/s at the end of 1994. The flow rate demonstrates a smooth and continuous relation with time.

In the same vicinity, 3 additional boreholes are used for water level and water temperature measurement. These boreholes have different depths. One borehole, which is a few meters away from the artesian well, is 40 m deep and the ground-water is 3 m below the surface. The water level shows a strong seasonal effect of several tens of cm. Two additional wells are 2 km away. One of them is 201 m deep, the other 2005 m. The water-table is 14 m, resp. 40 m below the surface. The first one exhibits a small seasonal effect which is not present in the latter. All of the three boreholes

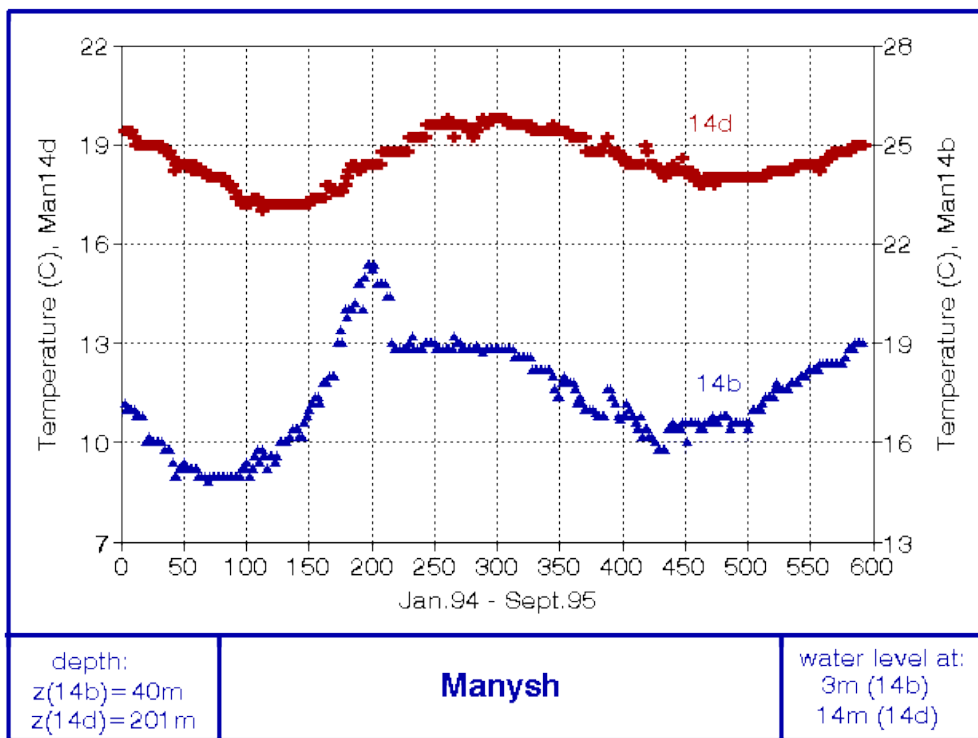are influenced by a regional flow which is assumed and shown

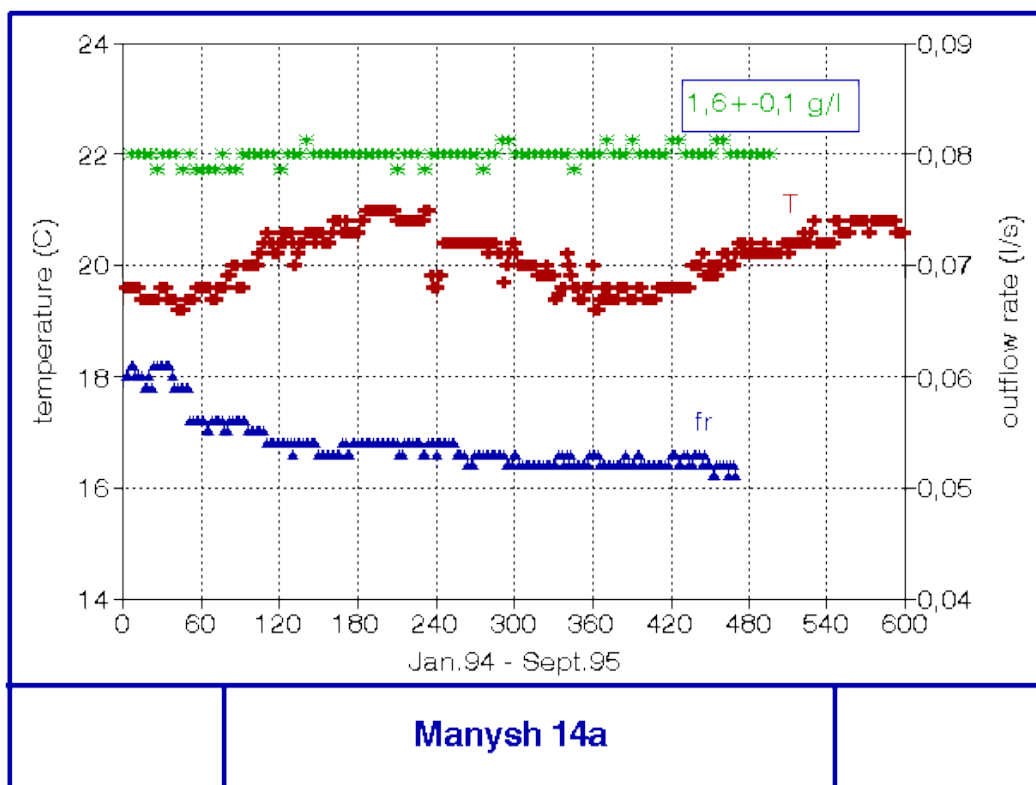Fig. 8: *Temperature at the water-table of Manysh boreholes at different depths (m), monitored every 5 days*

Fig. 9: *Temperature, salt content and the flow rate at the artesian Manysh borehole (no.14a), controlled every 5 days*
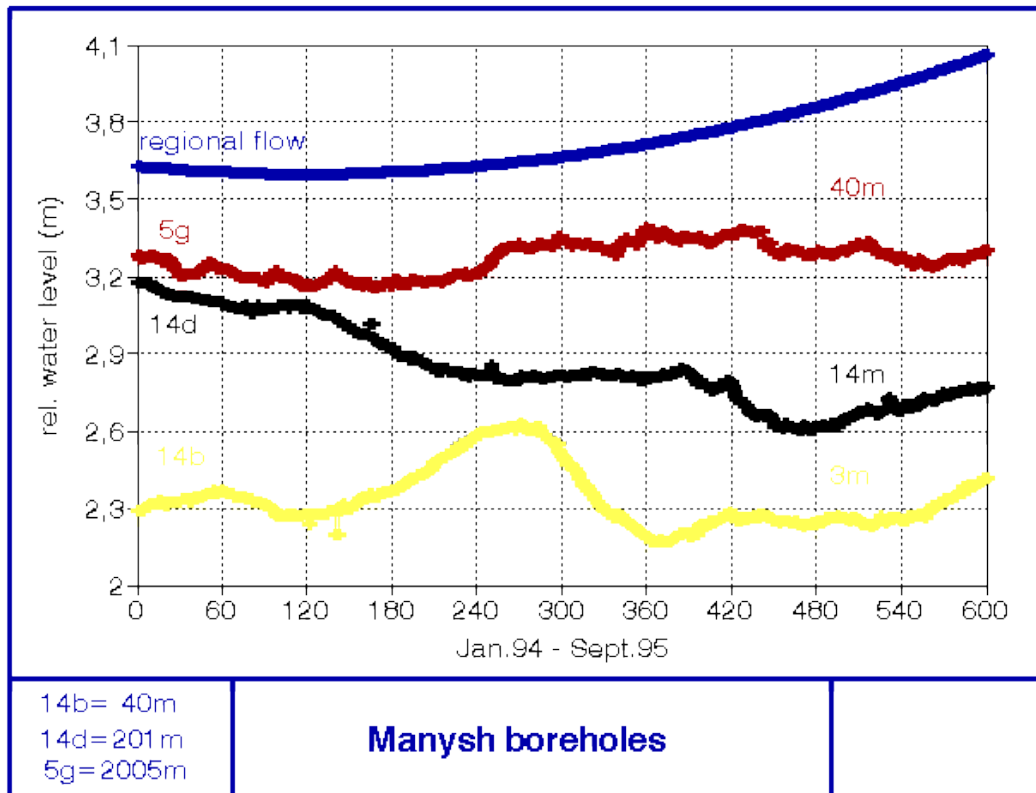
Fig.10: *Water level of Manysh boreholes of different depths (m), continuously recorded. A supposed regional flow has been subtracted from the data.*

in fig. 8 and already subtracted. The water level records do not demonstrate any relation to the weak earthquakes which occurred in the region, neither, in general, does the temperature at the water-table which is strongly influenced by the annual variation. One exception exists with the 40 km deep well (no. 14b) which demonstrates a pulse of 1.5 °C during July 1994. This occurred 4 weeks before an earthquake swarm with magnitudes of about 2.5 to 3. The epicenters were approximately 20 km away. However, all the other boreholes were not affected by this seismic activity.

Conclusion

The temperature in a borehole not only reflects the basic heat flow from the deeper crust, but also local effects which allow the water to move, create a barrier or cause a migration of the pore fluid. The high variability of the petrophysical properties within a borehole also results in very different effects, if some stress develops and causes the water to move. The few boreholes which were considered demonstrate that the amplitude and the width of its half value vary not only with depth within a borehole, but also with the total depth of the borehole. The reason might be that an aquifer can discharge water or is able to store some volume of water, i.e. it acts as a buffer. If the thermometer is too far from a discharging layer, the transported heat may dissipate before reaching the sensor.

These observations are in agreement with the literature where the different influences of tectonic activity on the temperature field is reported, but the reasons are poorly investigated. In most cases, the temperature gradient provides more detailed information on stress variation than the temperature itself. All earthquakes for which some deformation of **10-12 at the sensor is estimated cause some kind of jerk, excursion or step in the temperature at some depth within a

borehole.

At the water-table, the precursory phenomena cannot be recorded in general. The gradient varies with several tens of milli-Kelvin per km, and in most cases a few days prior to the seismic event. There are arguments that strong earthquakes are prepared over a long period of time, as demonstrated by the measurements at Didiweli and Manysh. This effect was already reported by Shimamura (1983) who concluded that the temperature steps in a borehole correlate with the distance from the epicentre and with the magnitude of the earthquake. However, the data are still insufficient to establish an analytical relationship. Shimamura (1983) concluded from his records that a coeismic termperature signal does not correlate with water level, because

$$\frac{\Delta p}{\Delta t} \approx \frac{\Delta T}{\Delta t} \quad (3)$$

If the temperature and the water level variation of the Manysh boreholes are compared with each other, some correlation can be seen at the shallow well only. The reason is that with deeper boreholes the relationship is more complex, because a sequence of layers and several aquifers might be involved. A weight function must be added to the relationship above which is inversely dependent on the depth (d). From this consideration, it follows that

$$\frac{\Delta p}{\Delta t} = f\left(\frac{1}{d}, \frac{\partial T}{\partial z}, \frac{\partial T}{\partial t}\right) \quad (4)$$

which also means that *p/*z is also a function of the temperature gradient:

$$\frac{\Delta p}{\Delta z} = f\left(\frac{\partial T}{\partial z}, \frac{\partial T}{\partial t}\right) \quad (5)$$

A complex sequence of permeable layers which are encountered within a borehole needs a multisensor system for microtemperature measurements in order to hit those aquifers which are sensible to tectonic stress variations. A quantitative relationship between stress and temperature variation can only be established for each individual borehole. According to the recent results, an overall law which involves a large number of data would reflect only average values in the same way as the estimation of the deformation during an earthquake does.

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