NEOTECTONIC ACTIVITY INTERPRETED FROM A LONG WATER-TUBE TILTMETER RECORD AT THE SRC GEODYNAMIC LABORATORY IN KSIĄŻ, CENTRAL SUDETES, SW POLAND

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ABSTRACT

A water-tube tiltmeter system composed of two perpendicular tubes was installed in the underground galleries of the Geodynamic Laboratory in the Książ Castle, Central Sudetes, in 2003. The partially filled water tubes are several tens of metres in length and have high-precision interferometric recording gauges at their ends. The recording gauges continuously measure water level changes in the tubes with single-nanometer accuracy which corresponds to 0.005 milliseconds of arc of plumb line variations. The tiltmeter has recorded several events of water level variations, with a magnitude of a few hundred micrometers and a duration of tens of days. The strongest water level variations were one order greater than variations caused by tidal phenomena and occurred in different months of a year, and hence are expected to have no seasonal origin. Because of the extremely large magnitude of the phenomenon and because time of duration of signals showed no seasonal characteristics, all external sources outside the bedrock space occupied by the instrument can also readily be precluded.

Each of the recorded strong signals of water level variations consists of a symmetrical and an asymmetrical component. Because of the proportion of the water system to the large-scale geodynamic sources producing water level changes, all the external geodynamic reasons can generate only symmetrical signals in the tubes.

The evidence indicates episodic tilting of the instrument itself or vertical displacements of any part of the tubes, which supports the notion of active bedrock deformation. The combination of symmetrical and asymmetrical signals implies that their source is within the bedrock space in which the instrument is embedded. The events of large water level variations can be explained by non-flat relative vertical displacement of the opposite ends of the tiltmeter tubes. Asymmetrical signals are particularly pronounced in the tube named 03-04, and their magnitude suggests vertical displacement of part of the tube of the order of hundreds of micrometres. The repeatability, temporal irregularity, considerable duration time and high magnitude of the strong signals lead us to attribute them to the tilting of tiltmeter bedrock due to contemporary tectonic movements of the Książ Massif.

The Książ Massif consists of a rigid rock mass of Famennian−Tournaisian conglomerates cut by several large and small faults. Rock compaction can be precluded. The massif is a prominent bedrock spur carved by a deeply incised river, and its geomorphic development seems to be related to major faults. Preliminary geological study has recognized strike-slip faults, thrusts and extensional fracture zones, some with an indication of recent activity. A few minor faults cross the bedrock under the tiltmeter geodynamic system. The tiltmeter is thus likely to be recording local signals of neotectonic activity.

KEYWORDS: bedrock, fault blocks, neotectonics, non-tidal signals, water-tube tiltmeter, signal filtering

INTRODUCTION

This paper discusses further the phenomenon of strong non-tidal signals recorded by the WT tiltmeter equipment at the Książ Geodynamic Laboratory (KGL) and reported earlier by Kaczorowski (2007, 2009a, b), Michelson and Gale (1919), Kukkamäki (1965), Kääriäinen (1979) and Ruotsalainen (2008). The main advantages of a WT tiltmeter with free water surface over other tiltmeter types include its stable sensitivity and a high and stable resolution of measurements (over two orders of magnitude higher than from a horizontal pendulum), its precise determination and stability of measurement azimuth, a lack of instrumental drift (which occurs hen a differential method is applied), a wide band of registered signals and the instrument's extensive groundwork with a measurement space of close to a hundred metres (Bower, 1973; Kaczorowski, 2006). The measuring system consists of two perpendicular tubes 01-02 and 03-04 that are ca. 90 m and 65 m long and oriented at 58.6° and 148.6°, respectively. Since their installation in 2003, the WT tiltmeter system has recorded several events of remarkably strong water-level changes (Kaczorowski, 2007, 2008). The greatest changes reached several hundred micrometres and occurred without any obvious seasonal correlation. The Książ Massif is not saturated with water. The nearest mountain stream Pełcznica has a typical flow of 1 cubic metre per second and has a very narrow valley. Therefore within the surroundings of the laboratory there is no effect of large water mass concentration (Kaczorowski, 2007).

The strongest events lasted for one to two weeks and the recorded signal invariably had three recognizable components: the tidal signals, water evaporation signals and a puzzling, strong asymmetrical signal presented in this paper.

GEOLOGICAL AND GEOMORPHIC SETTING OF THE KSIĄŻ MASSIF

The Książ Massif is located in the central part of a structural geological unit known as the Świebodzice Depression/Basin, which belongs to the regional mosaic of evolving Sudetic Palaeozoic sedimentary basins (Oberc, 1978; Żelaźniewicz and Aleksandrowski, 2008). The structural unit, as seen today, is a fault-bounded, tectonically cut-out fragment of an originally larger Famennian-Tournaisian sedimentary basin (Nemec et al., 1980; Porębski, 1981, 1997; Ziegler, 1990). The rhomboidal Świebodzice unit (Fig. 1A) is separated by the Marginal Sudetic Fault from the Fore-Sudetic Block to the northeast, by the Szczawienko Fault from the Sowie Góry Gneissic Block to the south, and by the Struga Fault from the Intrasudetic Basin to the southwest. The unit's northeastern boundary with the metamorphic rock complex of the Kaczawa Mountains is less well defined, marked by a system of minor faults (Sawicki, 1955; Gunia, 1968; Teisseyre, 1969; Haydukiewicz et al., 1962; Bossowski and Czerski, 1985; Walczak-Augustyniak, 1988; Teisseyre and Walczak-Augustyniak, 1988).

The Książ Massif is cut by numerous faults (see the main ones in Fig. 1B), and several of them intersect the KGL underground tunnels and run obliquely to the orientation of the WT tiltmeter tubes (Fig. 1B). The angle between the faults and tubes 03−04 and 01−02 is about 75º and 25º, respectively. At least three of the active extensional faults, striking NE−SW, show clayey gouge and a young, possibly Recent, mineralization. Moreover, they are accompanied by a number of complementary structures, such as the Riedel fractures or slickensides and silicolithes, which are good kinematic indicators (Fig. 2)

The Książ Massif forms a structural-morphological spur, curved out in the rocks by a large bend of the Pełcznica River that flows here in a 100-m deep canyon (Fig. 1B). The spur extends towards the WSW between two main mapped faults, with its longitudinal foot-slopes and flanking river segments almost perfectly matching the fault lines (Fig. 1B). The spectacular bend and deep incision of the Pełcznica River and the resulting bedrock spur of the Książ Massif are apparently related to the faults and may indicate their recent activity.

Therefore, it is likely that the strong signal of water level variations recorded by the WT tiltmeter embedded in the Książ Massif originates from the geodynamics of the local bedrock structure and reflects active regional tectonics.

THE RECOGNITION OF DRIFTLESS NON-TIDAL SIGNAL IN A WT TILTMETER RECORD

In order to recognize long period or systematic signals, it is necessary to remove from raw observations all kinds of signals of tidal frequency, as well as drift signal of evaporation effect from the hydrodynamic system of a tiltmeter.

The effect of water evaporation is a main drift component of a WT tiltmeter. Other components of instrumental drift are small enough to be neglected in the further discussion.

Drift signal of evaporation does not interfere with other signals, tidal or non-tidal, and can easily be separated. Due to small temperature changes of ~0.1°C and relative humidity variation of ~1% at the measurement site on a time scale of several days (Kaczorowski, 2008), the evaporation of water from the tiltmeter's hydrodynamic system is very gradual and its time function is linear. The average speed of the decrease in water level during events of strong water level variations amounts to 2.5 micrometers per day. For comparison the average amplitude of water level variations caused by tidal signal is 65 micrometers in tube 03-04.

It is thus justifiable to assume that the evaporation rate on this time scale is constant, and that the speed of evaporation during strong non-tidal signals remains the same as during at least the preceding few days. In our discussion, shortening or lengthening of the tubes caused by thermal or strain effects has been omitted because water level changes associated with tube deformations are proportional to the ratio of tube radius to its length (10^{-5}).

The coefficient of the evaporation function determined just prior to a strong event should then be valid also for the short time duration of the event. Since large-scale tectonic movements act as an external source and their signal is symmetrical (Kaczorowski, 2009b), the function of evaporation is taken to be an arithmetic mean of signals at the opposite ends of the tiltmeter tubes from the preceding few days. The tidal signal has been filtered out from the raw instrumental record by using the ETERNA 3.4 software (Wenzel, 1996) with HW95 catalogue of the tide generating potential (Hartmann, Wenzel, 1995). Additionally, we applied low-pass filter n60m60m2 for one hour data sampling which is suitable for the program ANALYZE of the ETERNA 3.4 package.

After a low-pass filtering of the record time series, one can recognize the signal of water-level change unrelated to tides, from which the water evaporation trend is further removed. During the measurement period of 2004−2007, we recorded five events of strong water-level change and the best-analysed three of them (Fig. 3) are selected here for

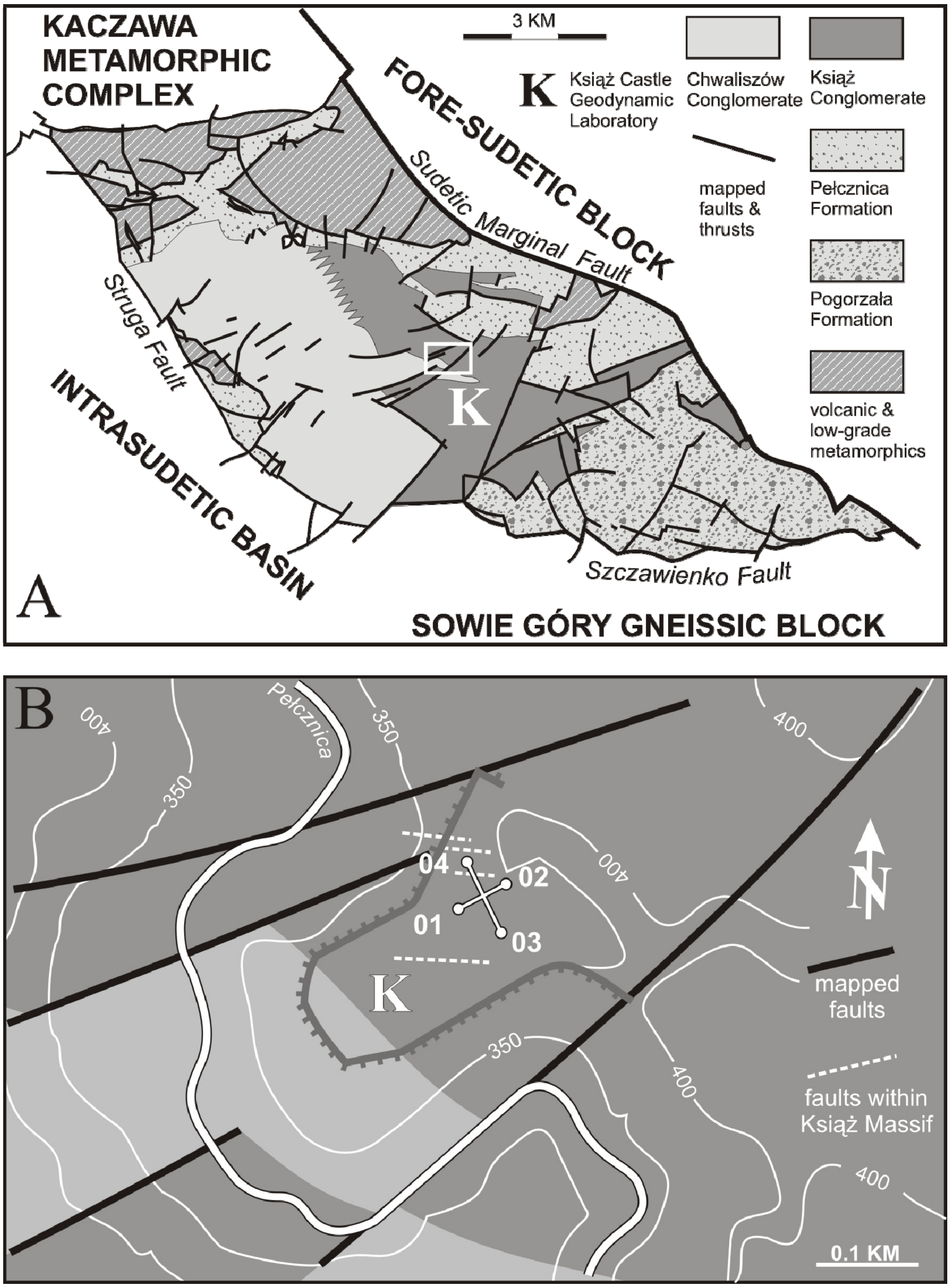

Fig. 1 Geological map of the Świebodzice geo-structural unit with the location of the Książ Massif where the tiltmeter instrument is embedded. (B) A geological and topographic map of the Książ Massif showing the location and spatial orientation of the tiltmeter tubes 01−02 and 03−04.

further discussion. As a matter of discussion on non-tidal signals, it is necessary to have complete records from four channels, therefore two events were omitted.

A stronger signal was invariably recorded in tube 03−04 (Fig. 1B) and the maximum recorded water-level change exceeded 650 μm. The events occurred at the time of autumn/winter and winter/spring transitions as well as in the mid-summer month of July 2006 (Kaczorowski, 2009a), which allows us to preclude influence of any seasonal factor. In 2006, large non-tidal water-level changes were recorded twice. In the discussion of the genesis of large water level variations all the hydrological effects have been omitted. The Książ Massif is not saturated with water and the nearest mountain stream Pełcznica has a typical flow of 1 cubic metre per second, while the river valley is a hundred meters wide only. Therefore in the surroundings of the laboratory there are no conditions for any accumulation of a large water mass. Signals which are discussed in the paper are not connected with the large flood in summer 2006 in the Oder river valley which is about 70 km away from Książ Laboratory. In spring 2005 a strong event of water level variations was one order greater than tidal signal and happened without any flood. Moreover, all large-scale phenomena can generate only symmetric signals of water level variations, and therefore cannot explain asymmetry between water level changes in opposite channels (Fig. 3).

ANALYSIS OF THE RECOGNIZED STRONG EVENTS

The removal of the tidal and instrumental drift signals from the data series has almost completely flattened the graphs for the time period prior to the strong event (Fig. 3). The graphs of water-level changes in tube 03–04 show clearly an asymmetry of the event signal recorded in channels 03 and 04, with a fall in the former and a coeval rise in the latter channel. The ratio of the magnitudes of asymmetrical and symmetrical water level changes is similar for all the strong recorded events (Fig. 3).

The remarkable asymmetry of the signal amplitude in tube 03−04 indicates that the causal factor of the strong water-level change was not a large-scale regional bedrock tilting, for which a symmetrical record would be expected. The asymmetry implies differential vertical movements within the bedrock space in which the tiltmeter tubes are embedded.

The water-level changes recorded in tube 01–02 are considerably more complex than those in tube 03–04 (Figs. 4–6), showing a recognizable change both prior to and after the strong change recorded in the latter tube. Just prior to the asymmetrical water level change in tube 03–04, the falling water level in channel 01 began to rise, while the rising water level in channel 02 began to fall (Fig. 4A). An opposite change occurred in channels 01 and 02 almost directly after the strong change in tube 03–04 (Fig. 4B).

A different pattern of water-level change was recorded in tube 01–02 after the strong change in tube 03–04 during the 2nd and 5th events (Figs. 4-6). The water level in both channels 01 and 02 fell simultaneously below the pre-event level, which suggests an uplift of both ends of the tube in relation to its medial part. No such in-concert changes have been recorded in tube 03–04 during any of the strong events.

SUGGESTED MODELS

In the ensuing discussion, we consider the instantaneous effect of a site-crossing single fault, with a vertical component of displacement, on the instrument's water level. For simplicity, we assume the following kinematic pattern of relative movement for both of the tiltmeter tubes: one half of the tube (taken to be the channel segment 03 or 02) is unmovable, whereas the other half (channel segment 04 or 01, respectively) is subject to a uniform downward displacement.

Le us first consider the kinematic model with a reference to the tilmeter tube 03−04. The relative lowering of its channel segment 04 by a vertical distance Δd will decrease the water level in the whole tube by Δh (Fig. 7), where Δd is the vertical component of displacement on the tube-crossing hypothetical active fault. The water-level change Δh will be recorded directly by the gauge of channel 03, whereas the gauge of channel 04 will record the corresponding difference ($\Delta d - \Delta h$). The assumption of water-mass conservation implies the following relationship:

$$\Delta d \cdot X = \Delta h \cdot L$$

where X is the distance from gauge 04 to the hypothetical fault and L is the length of tube 03−04 (constant). Any variations of water level inside the tube caused by shortening or lengthening of the tube are proportional to the ratio between tube diameter and tube length (10^{-5}); therefore we are able to exclude this effect from further discussion.

The vertical displacement on the fault is then:

$$\Delta d = h_1 - h_2$$

where h_1 and h_2 are the changes in water level recorded by the gauges of channels 03 and 04, respectively (Fig. 7).

An analogous single-fault model has been applied to the coeval record of water-level changes in tube 01−02 (Fig. 8). For three of the events, the single-fault model allowed an estimation of the distance ($X \approx 30$ m) from the channel gauge 01 to the hypothetical active fault. However, the model failed to give an equally clear solution for the two other events.

CONCLUSIONS

The tiltmeter's tube 03−04 is nearly perpendicular to the local faults and crosses at least one of them. A single-fault modelling of the system yielded an unstable solution for small changes in the water level, but gave a stable solution for large ones. The distance from the tube's gauge 04 to the hypothetical active fault is predicted as 58−62 m, which corresponds rather well with the local tectonic structure of the Książ Massif, although the tube's fault-perpendicular orientation tends to average the signal of the relative vertical movement of the underlying fault blocks.

The tiltmeter's tube 01−02 is nearly parallel to the local faults and its record indicates an upward movement of gauges 01 and 02 relative to the medial part of the tube. This evidence adds complication to the scenario of neotectonic activity in the Książ Massif by suggesting a greater kinematic heterogeneity, possibly involving unrecognized small cross-faults.

It is still an open question as to whether the recorded strong non-tidal signals reflect pure vertical bedrock movements. Since few of the mapped faults are strictly vertical, it is likely that the fault blocks are subject to 3D rotations, whereby only the vertical component of the actual block movement would be detected by the WT tiltmeter.

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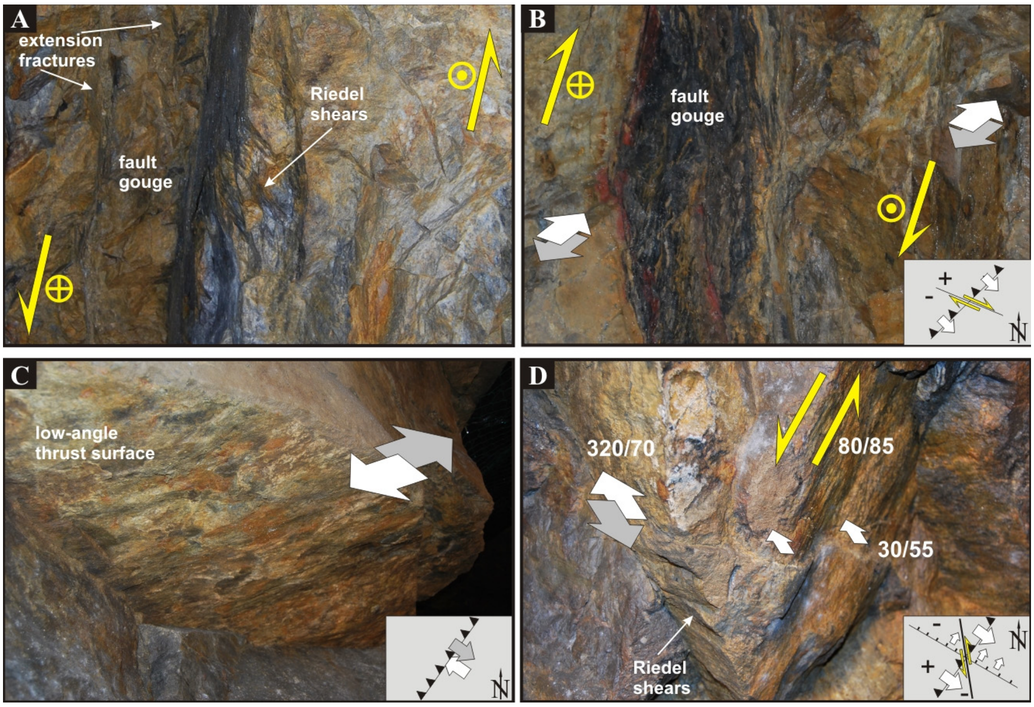

Fig. 2 Structural-tectonic features of the Książ Massif in the vicinity of the Książ Castle, where the tiltmeter instrument is positioned in underground tunnels. (A) Extensional fractures, Riedel shears and fault gouge. (B) A thrust fault with gouge. (C) A slicken-sided thrust surface. (D) Extensional features including Riedel shears. The inset diagrams are plan-view kinematic reconstructions of the corresponding tectonic movement.

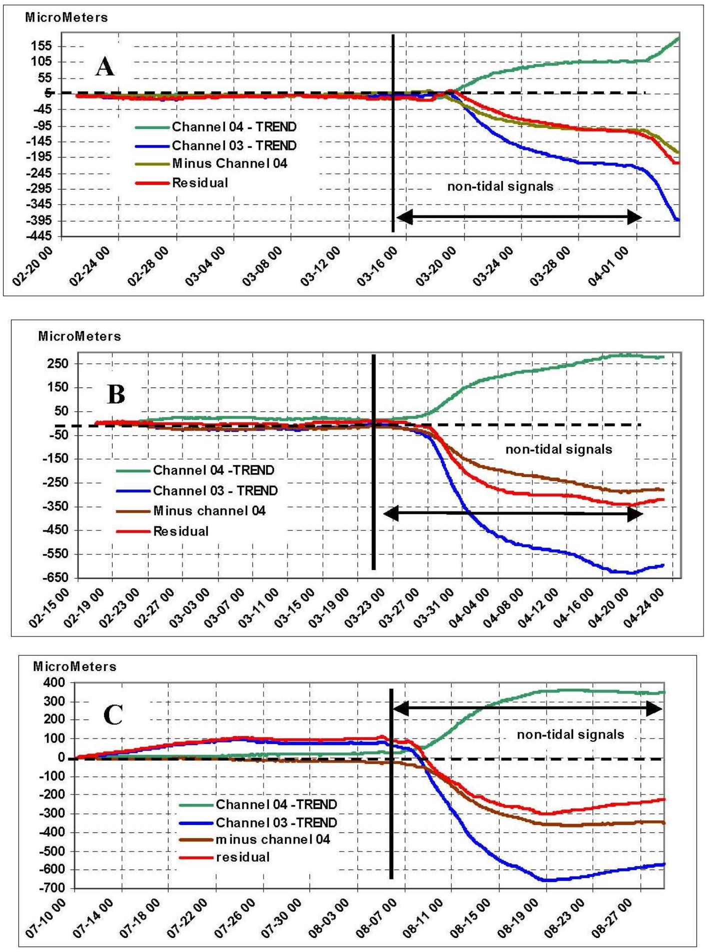

Fig. 3 The record of strong water-level changes in tiltmeter tube 03−04 after removal of tidal and evaporation signals: (A) the 2nd event, March 2005; the 4th event, March 2006; and (C) the 5th event, July 2006.

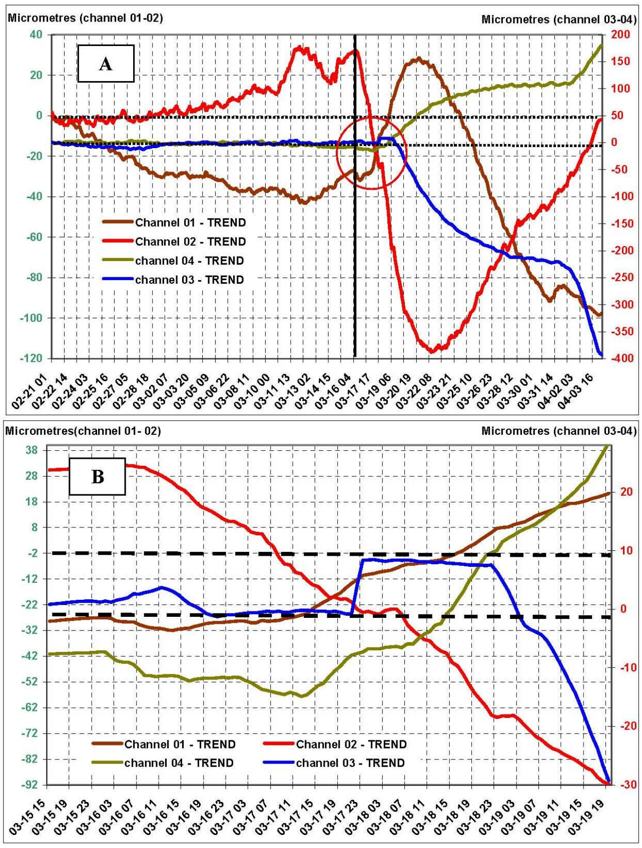

Fig. 4 The record of strong water-level changes in tiltmeter tubes 01−02 and 03−04 (the 2nd event, March 2005) after removal of tidal and evaporation signals. (B) Record from tubes 01−02 and 03−04, showing the beginning of strong signal in channels 03 and 04 and the coeval record from channels 01 and 02.

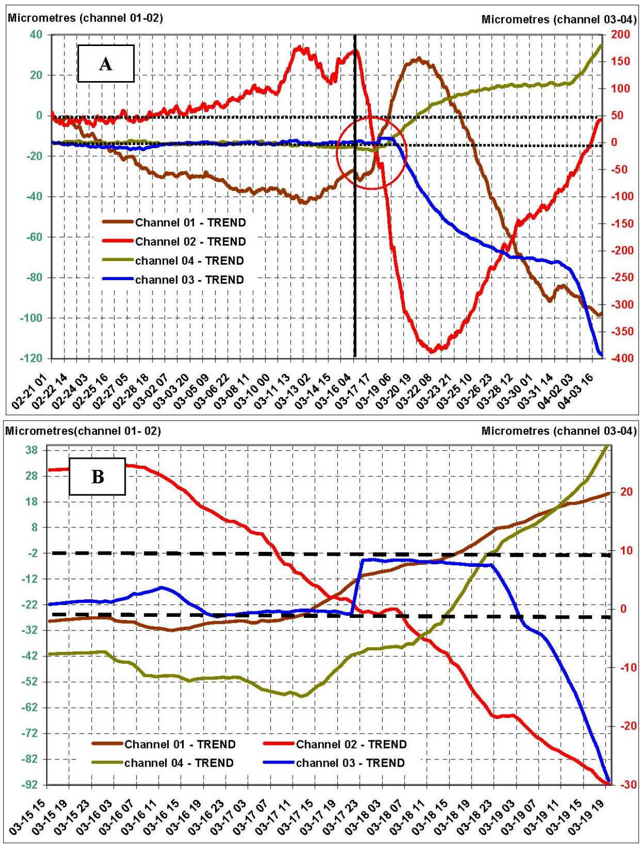

Fig. 5 The record of strong water-level changes in tiltmeter tubes 01−02 and 03−04 (the 4th event, March 2006) after removal of tidal and evaporation signals. (B) Record from tubes 01−02 and 03−04, showing the beginning of strong signal in channels 03 and 04 and the coeval record from channels 01 and 02.

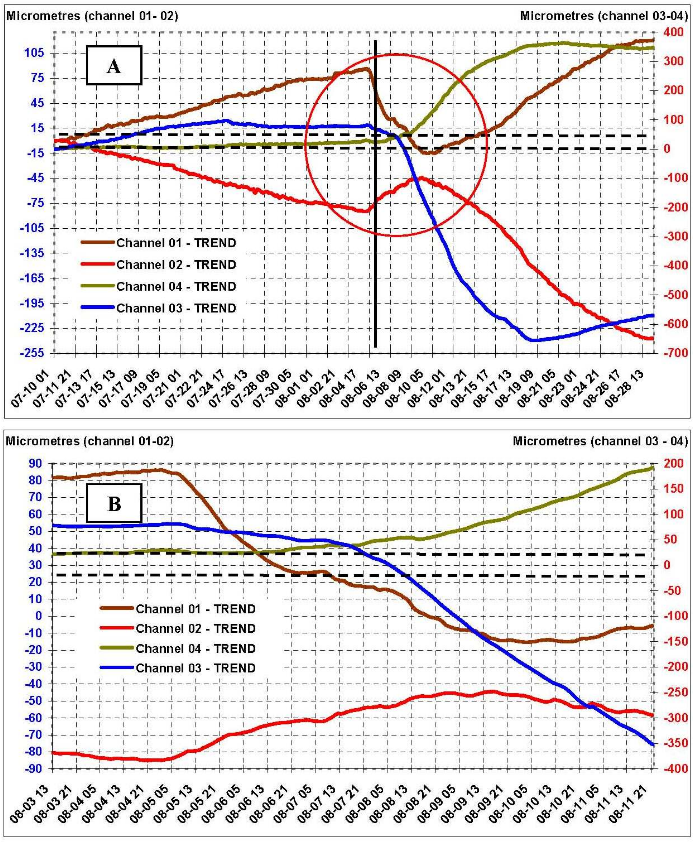

Fig. 6 The record of strong water-level changes in tiltmeter tubes 01−02 and 03−04 (the 5th event, July 2006) after removal of tidal and evaporation signals. (B) Record from tubes 01−02 and 03−04, showing the beginning of strong signal in channels 03 and 04 and the coeval record from channels 01 and 02.

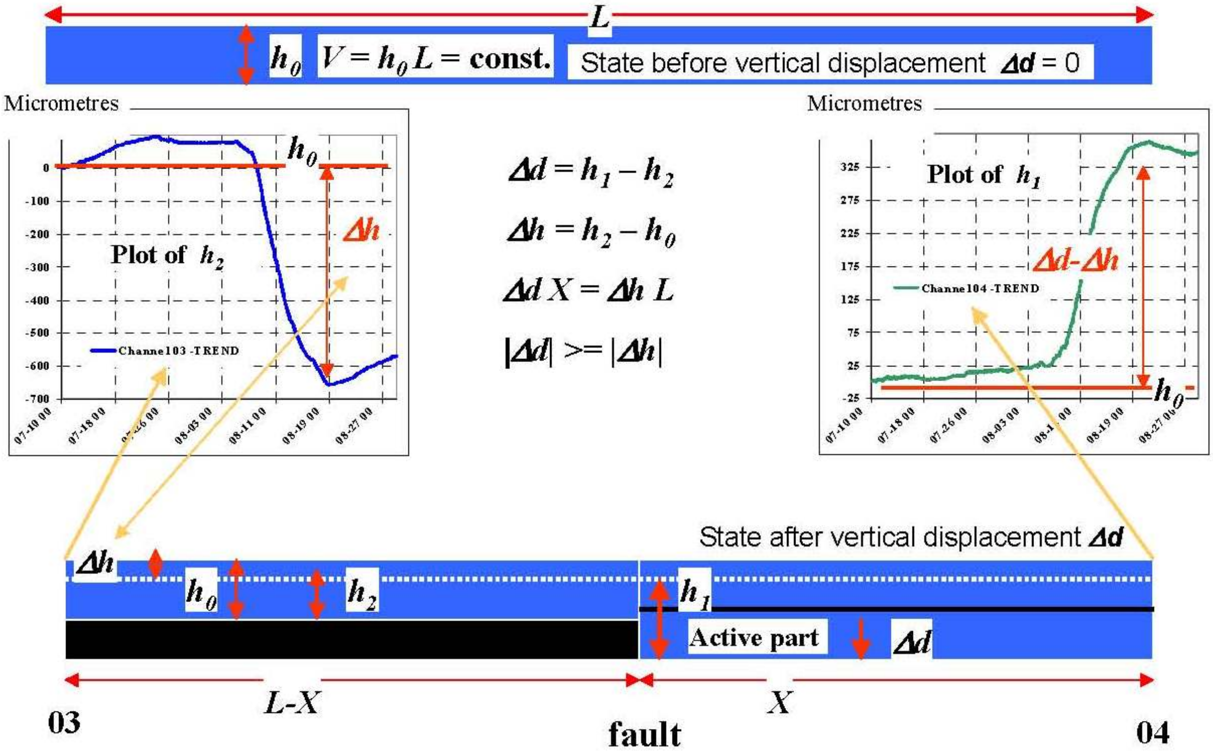

Fig. 7 A single-fault model of relative vertical displacement applied to the record of water-level changes in tiltmeter tube 03−04 during the 5th event (July 2006).

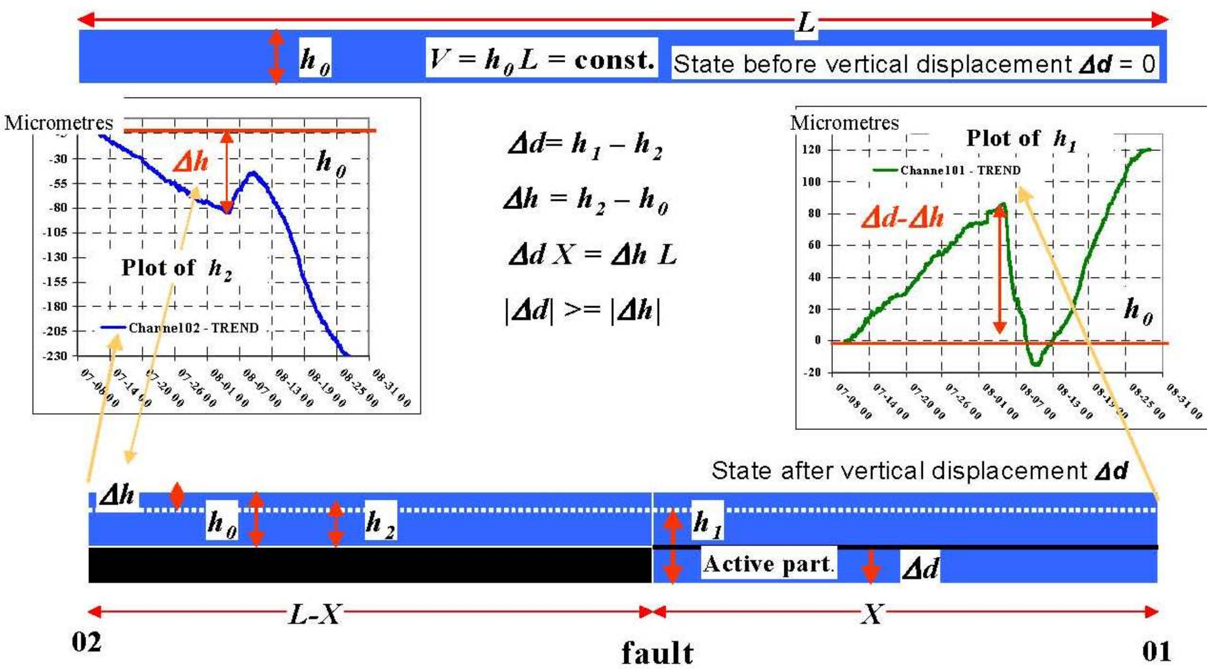

Fig. 8 A single-fault model of relative vertical displacement applied to the record of water-level changes in tiltmeter tube 01−02 during the 5th event (July 2006).