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# 3-D TREND OF ASEISMIC CREEP ALONG ACTIVE FAULTS IN WESTERN PART OF THE GULF OF CORINTH, GREECE

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## ABSTRACT

Quaternary faulting in the western part of the Gulf of Corinth has been evidenced by geology and geomorphology, as well as by seismic recording. A series of three main normal fault segments are aligned in a steep southern coastal zone of the gulf. These fault segments, 15 to 25 km long, have an average strike of 90° - 105° and a northward dip of about 50° - 75°. Selected fault points were equipped with 3-D crack gauges TM71 during 2002 to monitor movements along the fault planes here, as well as on another fault cutting through the small island of Trizonia near the opposite northern shore of the gulf.

Results of the monitoring present relative displacements induced by active tectonic movements. Generally, the movements recorded on the faults are characteristic of an aseismic linear creep in vertical, i.e. uplifting/subsiding in rates of mm per year due to uplifts of the Peloponnesian Peninsula. In 2003 a three months long period of fast acceleration of movements was recorded. During this acceleration phase displacements changed to skew uplifting/subsiding with a left-lateral horizontal component. Moreover, horizontal rotation of monitored blocks corresponding to a systematic westwards opening of the Gulf was observed with only single eastward opening episodes.

**KEYWORDS:** active tectonics, 3-D monitoring, fault movements, The Gulf of Corinth

## INTRODUCTION

Since 2002 precise movement monitoring of active faults in the Aigion region has started within the framework of Corinth Rift Laboratory Project (see Moretti et al., 2002; Moretti et al., 2003). A high resolution technique characterized by considerable long-term stability was applied here to detect displacements right on the contact of rock faces between the two fault blocks (Avramova and Košťák, 1986). Observation points were instrumened with a spatial dilatometer TM71 which is able to provide 3-D long - term measurements of micro-displacements on individual structures (Košťák, 1991). Monitoring sites were selected in collaboration with Dr. Isabelle Moretti using structural map of the southern margin of the Corinth Rift composed by Ghisetti et al. (2001).

This type of monitoring equipment is installed also on active faults in southern and central Europe, for example along Marginal Sudeten Fault in the territories of the Czech Republic and Poland (Stemberk and Štěpančíková, 2003), then in Rhein Graben fault zone (Fecker et al., 1999), in Bulgaria (Dobrev and Košťák, 2000), in Italy (Borre et al., 2003; Stemberk et al., 2003), in Slovakia (Petro et al., 2004), and Slovenia (Šebela et al., 2005).

## METHODOLOGY

Our detection of active tectonic movements in the field is based on an assumption that active fault zones as discontinuities will be characteristic of reduced strength and therefore supposed to react sensitively to stress transformations in the Earth Crust. Nevertheless, micro-deformations are to be considered and therefore a high precision equipment is needed to monitor even micro-deformations in prolonged periods of time. Moreover, 3-D registration will highly improve the quality of data, since lateral movements must be expected.

The instrumentation used is called spatial dilatometer or crack gauge TM71. It is aimed to detect any displacement between two faces of separate rock blocks. It works on the principal of mechanical interference, moiré. Due to this principle, which completely avoids any electrical analogy means, the gauge displays an extremely large long-term stability, and infallible performance under hard outdoor conditions. It means practically that values registered during periods of decades can be well compared. Besides, it provides three-dimensional results. These involve displacements on structures in *mm*, and time trends derived (rates in *mm per year*). Sensitivity of the system: 0.05 to 0.0125 *mm* in all the three space co-ordinates of displacement, and $3.2 \cdot 10^{-4}$ *rad* in angular deviations between separated bodies. Under field conditions where difficult outdoor effects must be considered, an experience shows that the accuracy in data interpretation of 0.03 *mm*, and at least 0.1 *mm per year* can be generally reached. Such an unambiguous interpretation of results can be usually made on a condition that measurements continue for three years, at least, with about monthly reading frequency.

The ability to register lateral and shear displacement components is essential. Most of the discontinuities under investigation are under transversal pressure, which minimise the transversal effects. It is therefore shear, which is most applicable in the interpretation.

The system represents means for detailed measurements. It has been used autonomously, as well as in connection with other types of monitoring, namely GPS and other precise geodetic measurements like precise levelling, rangefinder measurements, or tape extensometry. In that the importance of higher frequency of measurements must be always considered since low frequency may disqualify the results. However, many types of measurements are so expensive that applied frequency can be too low. Seasonal effects cause irregular displacements in massifs that affect confidence limits. Therefore, only higher frequency of campaigns may be successful.

Our experience confirms a view that detailed measurements cannot be substituted. As compared with other systems, TM71 is extremely stable in nature and readings are simple. When considering the climate in such a Mediterranean country like Greece, high and low temperatures will often alternate with torrential rains and relatively long dry periods. Such conditions will affect the massif intensively and the instrumentation applied in the terrain is to be able to survive.

Measurement sites equipped with TM71 crack gauges (strainmeters, dilatometers) produced by GESTRA Sedloňov, Czech Rep. were established successively in quite different situations, underground in caves and galleries, on the surface in rock massifs, on slopes and in gullies, where a contact between two blocks is to be investigated (Košťák, 1991).

## TECTONICS AND GEOLOGY OF THE STUDIED AREA

The Gulf of Corinth represents about 130 km long graben, where according to Sérbier (1977) the southern coast is uplifting contrary to subsidence of the northern shore of the gulf. According to this, the slopes forming the southern margin are steeper with inclination in the range 30 to 45°. Slopes correspond to major faults with trend generally WNW – ESE, parallel or subparallel with the coast. Close to Aigion, there are three major, morphologically expressed faults – Pirgaki, Heliki (in prolongation to E as Lakka fault) and Aigion faults.

The Gulf of Corinth has been formed during the Quaternary as aproximately W – E extensional structure. The total extension through the whole Aegean region derived from satellite geodesy was estimated by Reilinger et al. (1992) by *4 – 5 cm/year.* During Quaternary, vertical movements between sea bottom and onshore peaks reached over 3000 m which corresponds to an average rate of relative uplifting/subsiding about 5 *mm/year* (Brooks and Ferentinos, 1984). The rate of tectonic uplift has been confirmed also by Armijo et al. (1996) from the investigation in sequence of marine terraces near the city of Corinth, which correlated with worlwide chronology of Pleistocene sea level changes. They suggested a slip rate of 11 ± 3 *mm / year* for the last 350 000 years. On the Aigion fault, the current slip rate should be 2 – 5 *mm/year* and the vertical offset is about 150 *m*; this suggests an age of less than 70 000 years (Micarelli et al., 2003).

Active tectonic movements are connected with an impressively high seismic activity in the studied area. Generally, the Aegean region is seismically very active and the Gulf of Corinth belongs to one of the most active parts. Historical seismicity was studied among others by Papazachos and Papazachou (1997). Recalling the most recent events destructive earthquakes occurred in 1981 and were associated with movements along normal faults at the eastern end of the Gulf (e.g. Jackson et al., 1982).

In the western part of the Gulf a stronger earthquake occurred in November 18, 1992 (magnitude Ms = 5.9, depth h = 7.5 *km*) and the epicenter was probably between Helike and Xylocastro faults - Xylocastro fault is situated in eastward prolongation of Pirgaki fault (Hatzfeld et al., 1996). And less than one year later (1993, July 14) the earthquake of Patras occurred and caused significant damage (magnitude Ms = 5.4). The main shock was connected with a strike-slip mechanism, left lateral on a NNW-SSE trending fault, and not on E-W normal faults generally seen in the Gulf (Hatzfeld et al., 2000).

The Aigion earthquake of 1995, June 15, was the strongest event (magnitude Ms = 6.2) after the 1981 shock in the Gulf, and was studied by Bernard et al. (1997). Main shock started on an E - W striking normal fault (north-dipping, angle of 33°) at a depth of 10 *km* and was relocated to the S towards the surface. The earthquake could be related to the Helike fault or to another one further north - offshore. Earthquake located beneath the northern shore usually indicate extensional slip on roughly E-W striking and 20° – 40° north dipping planes (e.g. Bernard et al. 1997). Fault planes exposed at the surface in the Aigion area, like the Heliki fault (Photo 1) are considerably steeper and dip values in the range 55°-70° can be observed.

During monitoring time, mostly earthquakes with magnitude in range 3 – 4 were registered. The strongest earthquake in NW part of Peloponnesos was registered in June 1, 2003, with M = 4.8 and epicentre offshore in western part of the Gulf, about NE from Aigion.

Progressive east-to-west opening of the Gulf of Corinth has been proposed by various authors (e.g. Sakellariou et al., 2001). As Moretti et al. (2003) conclude, there is no available data offshore to confirm this model, and onshore available data are sporadic.

**Photo 1** Overview of Heliki fault scarp from the Gulf of Corinth.

## MONITORING SITES AND INSTALLATION SPECIFICATIONS

Six dilatometers TM71 were installed along the three remarkable faults (Heliki, Lakka and Aigion faults) situated on the north bank of Peloponnesos and one dilatometer was installed on the fault crossing the Trizonia Island near the northern bank of Corinth Gulf (Trizonia fault). The position of the instruments on the main faults is presented in Figures 1, 2 and 3. Installation was finished and regular monitoring started in August 2002.

### ***HELIKI FAULT***

Heliki Fault according to Stewart and Vita-Finzi (1996) is composed from several parts (discontinuous segments) with total length of about 6.6 *km*. Fault direction is generally about 100° (range from 82° to 125°), fault plane dipping 55 – 70° to the north. The Heliki Fault crosscuts the Gilbert-type delta fan formed by a complex of hundreds meters of conglomerate sediments. On the fault surface there are remarkable vertical striations in correspondence with the dip of the fault plane. The Heliki fault displays a maximum vertical offset of approximately 700 – 800 *m* (Ghisetti et al., 2001).

Various authors came to calculate slip rates on the basis of the age of Heliki fault scarp. Pantosti et al. (2002) assumed a minimum slip rate of 2 *mm/year* and estimated the age of about 300 – 325 *kyear*. Armijo et al. (1996) and De Martini et al. (2002) obtained the age of about 120 – 130 kyear with a slip rate of 5 *mm/year*, however Armijo results should be possibly considered valid only for the eastern part of the Gulf.

There are three monitoring sites, which were instrumentd along this fault. Two sites are situated in nature just on the fault plane, the third site is situated on cracks disrupting an irrigation channel made of concrete.

#### ***SITE H2 – A GULLY NEAR THE ROAD DIAKOFTO - AIGION***

A fault plane N 100°55°N cutting conglomerate rock blocks (Upper Quaternary) exposed vertically in the gully was instrumented in the western wall. The gauge was fixed by iron bars to the neighboring blocks. The site is in a zone closely behind the main fault plane of the Heliki fault near the place where a paleoseismic trench was dug on the Heliki fault.

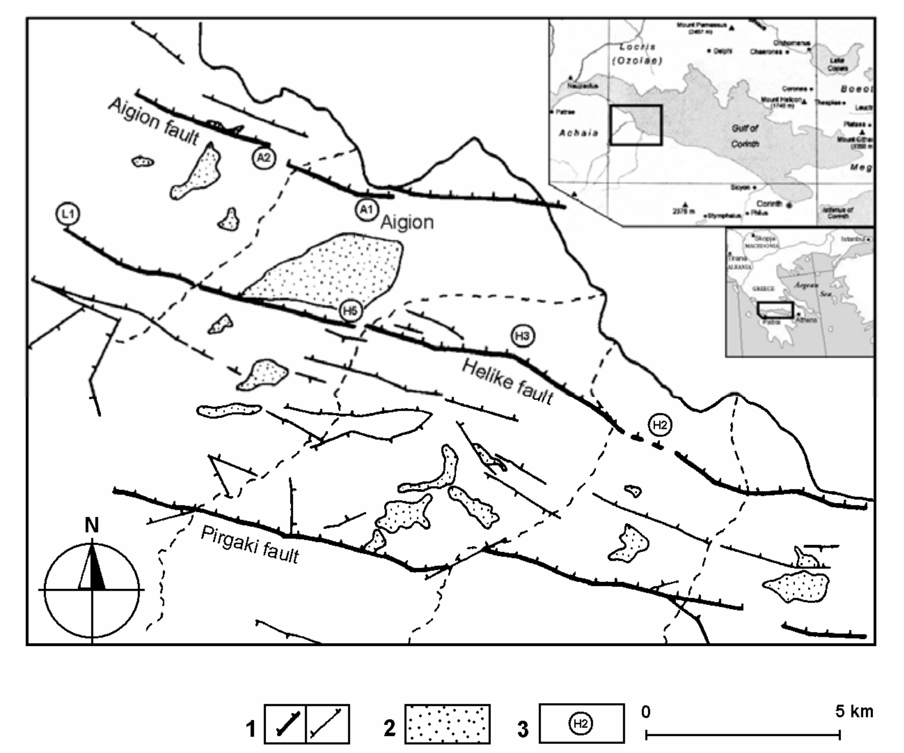

**Fig. 1** The map of south-western shore of the Gulf of Corinth (modified from Ghisetti et al., 2001). Explanations: 1) main faults, minor faults; 2) continental to marine terraces; 3) TM71 instrumented sites.

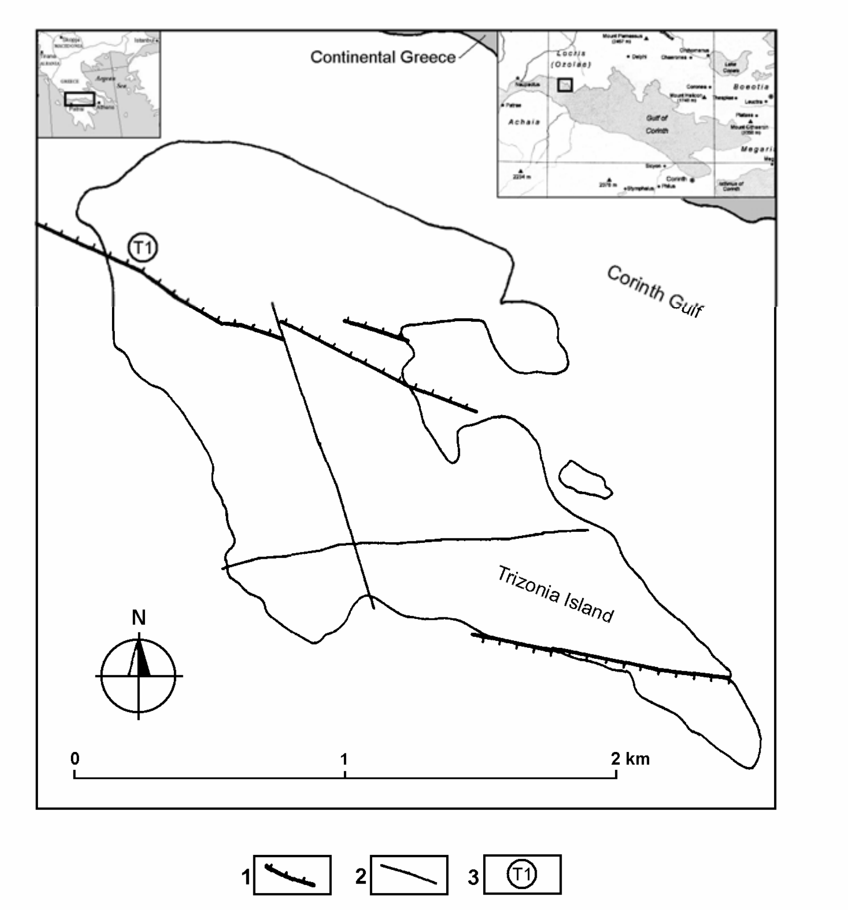

**Fig. 2** The map of Trizonia Island (modified from Moretti et al., 2002). Explanations: 1) main faults; 2) minor faults; 3) TM71 instrumented sites.

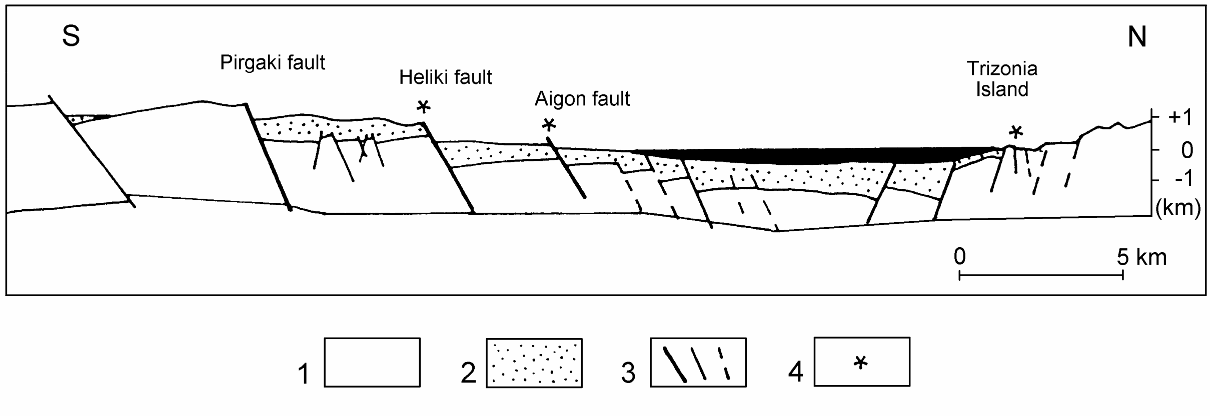

**Fig. 3** Cross profile through the western part of Corinth Gulf with monitored Heliki, Aigion and Trizonia faults. Explanations:
1) main faults/minor faults; 2) pre-rift sedimentary; 3) syn-rift sedimentary;
4) TM71 instrumented faults.

### *SITE H3 (NEAR THE TOLL ROAD CORINTH – PATRAS, SW FROM HELIKI VILLAGE)*

Fault plane: N 082°58°N with clear striation 022°/53°N. A contact of the tectonic mirror with its foreground was instrumented here in a trench bridging the foreground with the mirror plane of the Heliki fault (Photo 2). The instrument was fixed to the foreground in about 1.5 *m* deep trench with a concrete block bridging by an iron bar to the mirror plane.

### *LAKKA FAULT*

Lakka fault represents a westward prolongation of the Heliki fault.

Site L1 (S from the Lakka village)

Fault plane: N 090°50°N

A contact of a tectonic mirror with its foreground was instrumented in a trench just across the main fault plane of the Lakka fault. The trench is about 1 *m* deep and the gauge fixed into a concrete block in it by an iron bar on one side and into the wall plane on the other side. The fault plane is formed by carbonate and striations inclined to the west well conserved on fault plane just at the instrumented place. Block debris rims the fault slope toe. In the cross section of the monitored site one can observe clearly stretching-out of the debris along the fault plane.

### *AIGION FAULT*

Aigion fault (Koukouvelas, 1998) was recognised as a system of short, disconnected segments, dipping north 60°, with an average strike N100°. Just in Aigion City the fault is marked by a morphological fault scarp up to 100 *m* high. During 1995 earthquake, many parallel cracks damaged engineering structures along the fault.

### *SITE A1 – PORT OF AIGION*

The Aigion port is situated right at the foot of Aigion fault, under its remarkable scarp.

The port platform is visibly slanted toward to sea by about 3 – 4°. In the back part of it near the eastern coast line an open joint can be found in concrete separating the port platform from the shore. During 1995 earthquake cracks opened along the joint that come to reach a storehouse.

The joint represents a deep crack parallel with Aigion fault cutting through the floor of the large storehouse of the Aigion port mole. Traffic of heavy buggies does not allow precise measurements inside the storehouse. The joint on the embankment was instrumented therefore. Just under the installation site, a strong underwater spring in the seabed was recognised.

### *SITE A2*

Aigion fault continues from Aigion to the west cutting through the village of Constantinoundas. In this village during 1995 earthquake a parallel joint occurred. A series of cracks corresponding to Aigion fault were found directly in the body of a local drainage channel. A crack in the channel side wall was instrumented. TM71 crack gauge was fixed by iron bars across the crack. The crack is 0.5 to 0.7 *mm* in width with direction in the range of 105 – 110°.

### *TRIZONIA FAULT*

In the northern part of the Gulf of Corinth, faults are outcropping directly through the Cretaceous and Jurassic limestones. Trizonia Island with an area of about 2 $km^2$ is situated near the northern shore. In

**Photo 2** Heliki fault scarp close to Heliki village, place of monitoring site H3.

Trizonia Island, various faults have been recognized. The main fault, located in the central part of the island dips to the north and has an offset of about 300 *m* (Moretti et al., 2003). This fault constitutes the tectonic boundary between Lower Cretaceous-Turonian limestone and Senonian limestone. It crosses the island with an average N110-120°E orientation, dips about 50°N (Figs. 2, 3). The Trizonia Island appears to be a horst structure within the Corinth Graben. The activity analyses lead to a conclusion that main active faults dip mostly southwards and are located offshore.

Here a discontinuity was discovered on a slanted slope near the highest point of the island in a trench dug into the ground. The discontinuity was instrumented. Deeper in the trench the discontinuity was found as a deep open crack with N100E orientation and dip 45° N. The ground along the crack was not competent enough for the gauge to be set on firmly. Therefore cement pillars on both the sides were set for the gauge bridge.

## ANALYSIS AND EVALUATION OF RECORDED DATA

### ***HELIKI FAULT***

Data (Figs. 4, 5) obtained at the Heliki, site H3, can be analysed as follows:

*z (vertical component)*

mostly linear movements with average rate of 0.6 *mm/year* were recorded. During three months (April – July) in 2003, fast acceleration of movements was recognised. Acceleration had an exponential character and the displacement reach value of about 0.9 *mm*.

*y (horizontal component along the fault – strike slip component*

is mostly without movement. Only during the above mentioned period of vertical acceleration also horizontal movement occurred. The displacement in the period of acceleration reached a value of about 0.5 *mm*.

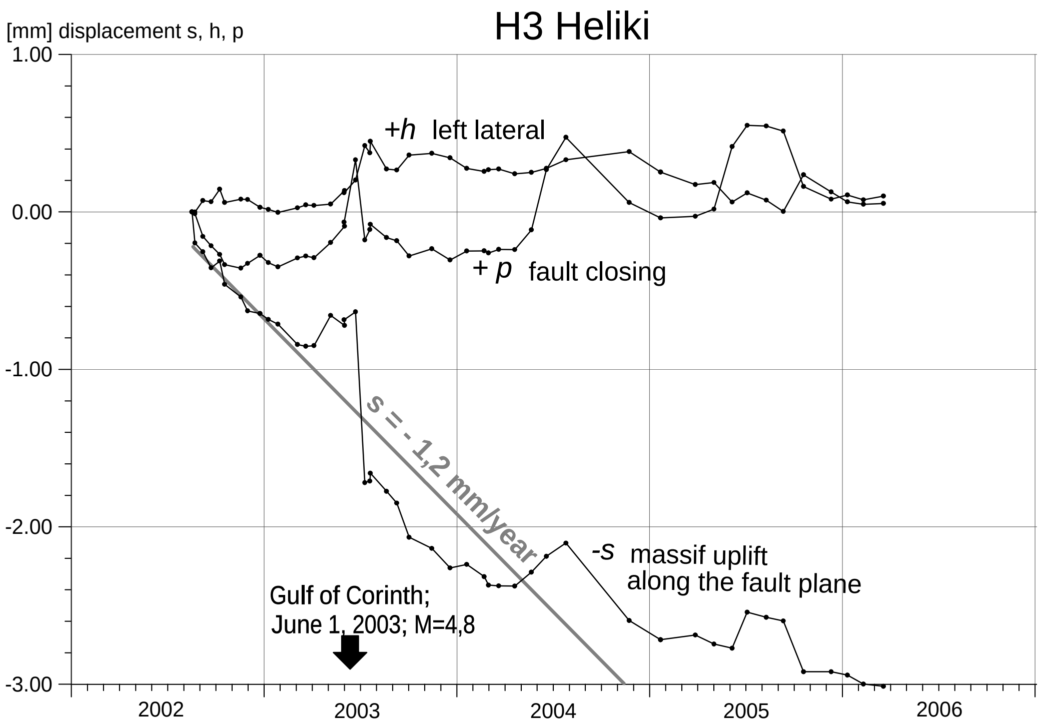

**Fig. 4** Displacements registered between 2002 and 2006 AD on Heliki fault, point H3.
A systematic uplift of the southern massif (Peloponnesos) was found.
In this graph Cartesian vertical oriented coordinates *x,y,z* are transformed into another Cartesian system *s,h,p* slope-oriented directly along the inclined fault, i.e. *s* – shearing up and down displacements (here Peloponnesos uplift); *h* – left-lateral movement; *p* – fault zone contraction.
Significant changes in all the three displacement components are joined with the local earthquake of June 1, 2003. The uplift *s* is evident; *h* and *p* movements are minor. Notice, that the uplift as well as left-lateral shifts were registered generally even at the other observation points (Figs. 6 and 7).

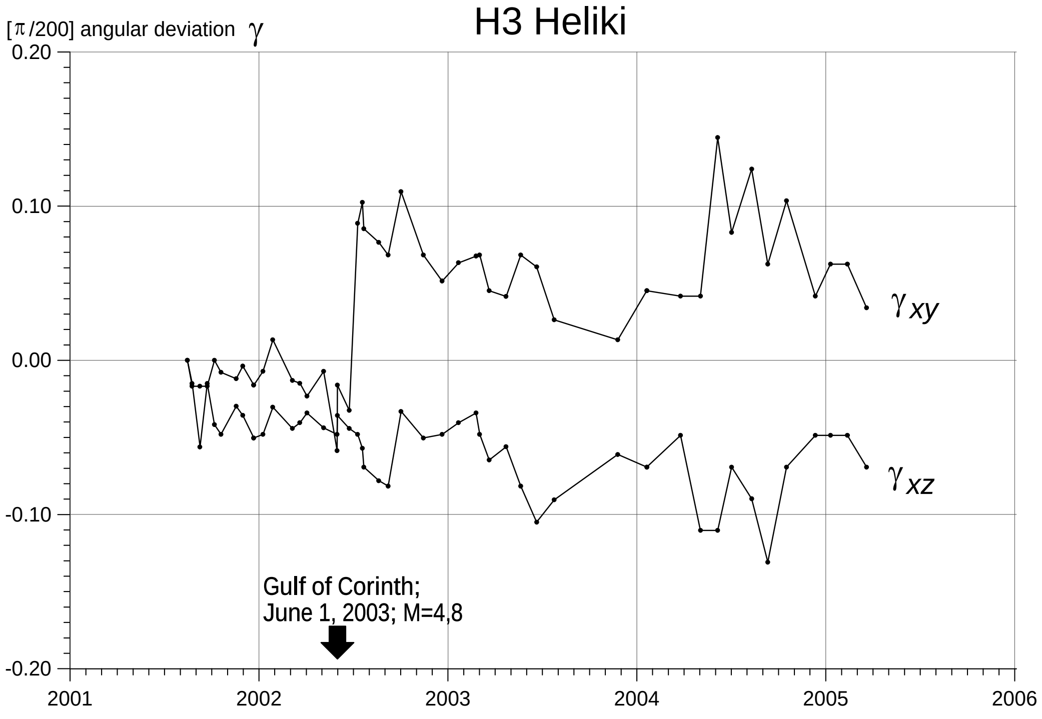

**Fig. 5** Angular deviations registered on Heliki fault, point H3.
Trend in angular deviation of the horizontal plane *xy* shows a systematic opening of the joint to Patras (W) with an abrupt opposite reaction in July 2003 – an after-effect of the local earthquake of June 1, 2003. Another episode of an opposite reaction in summer 2005 can be observed.

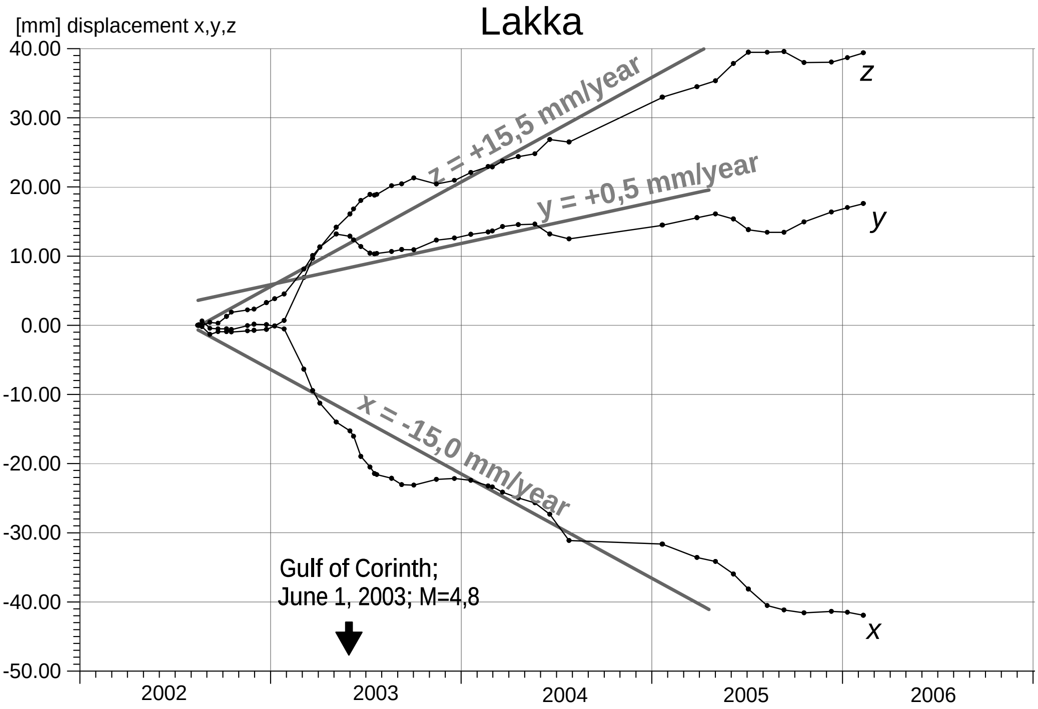

**Fig. 6** Displacements registered on Lakka fault, point L1.
Systematic trends are found in all the three displacement components: *z* – Lakka Mountain uplift, *y* – left lateral movement, *x* – extension in the fault. Remarkable S-like form in the diagram of *y* represents displacements that follow stress changes in the period of the local earthquake of June 1, 2003. They start considerably before and disappear slowly after the earthquake.

*x (horizontal component across the fault: fault – opening/closing)*

mostly linear opening was recorded. Opening reached a value of about 1.8 *mm* with fast movement at the end of the acceleration phase in 2003, when fault trench opened suddenly by about 1 *mm*. This relatively fast opening combined with the *y* movement was eastwards in the massif – left lateral, and closed the phase of accelerated movements.

### LAKKA FAULT

Data (Fig. 6) obtained at the site L1 (western continuation of Heliki Fault) can be analysed as follows:

*z (vertical component)*

August 2002 - January 2003 minimum movement was recorded. In February 2003 fast movement started and reached the value of about 33 *mm* till January 2005

*y (horizontal component along the fault – strike slip component)*

A linear movement was registered from the start of monitoring. An acceleration period January/April 2003 has been recorded followed by deceleration while movements turned back to mostly linear trend about 6 *mm/year* from July 2003.

*x (horizontal component across the fault – opening/closing)* the movement has started during February 2003 together with *z* Fast opening of the fault trench stopped in July 2003 and reached a value of about 22 *mm*. Since July 2003 the opening has been comparably slower.

*Generally,* we recorded relative uplifting of the hanging wall of the fault and possibly subsiding of its footwall. These vertical movements, known from geological data, were combined with a left-lateral component especially well pronounced between February and April 2003. Fast acceleration period of April/July 2003 observed at H3, has an analogy here at L1 as a period of a striking turn in the development of *y* and maximum movement rate in *x* (June 2003). Certain cyclic changes of seasonal character can be observed superposed to general trends.

Observations in angular deviations show a general tendency of opening of the fault to E. Angular deviation tendencies horizontal and vertical were largely modified during the acceleration of movements in the period January/July 2003.

## GENERAL DISCUSSION OF RESULTS

The gauges were installed on relatively narrow fault gaps and cracks related to Heliki, Aigion and Laka faults. It is clear, that it is not possible to

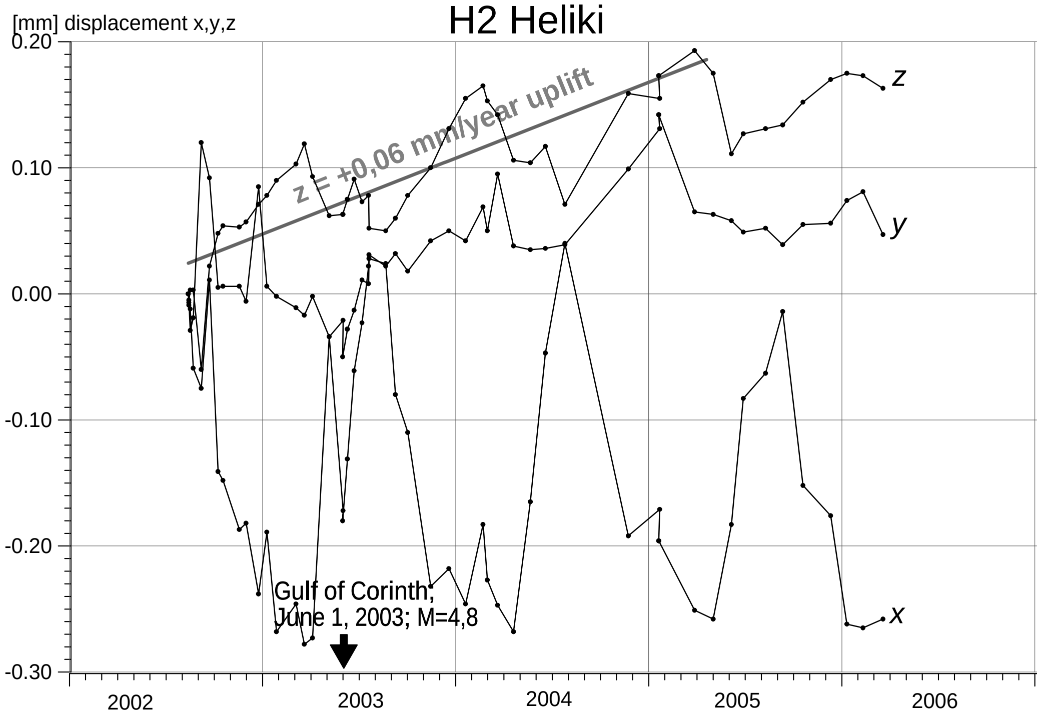

**Fig. 7** Micro-displacement registered on Heliki fault, point H2 in a gully.
Systematic displacements are found in two components: *z* – uplift of the southern massif, *y* – left lateral movement in the fault. All the three components suffer with seasonal dilatations in rock, which are most pronounced in variations of the transversal component *x* showing summer closing and winter opening of the rock joint. However, a conspicuous precursor of the local earthquake of June 1, 2003 can be observed in *x*, when a reversal movement occurred in May 2003, showing joint opening by 50% of the seasonal dilatation amplitude in the spring period othervise characteristic of standard joint closing.

monitor detailed 3D movements across the whole width of any fault zone. Micarelli et al. (2003) estimated the width of the fault zone pertinent to Heliki fault close to site H5 at 60 – 80 m with intensely deformed damage zone close to the main fault plane in a width of 10 m. With careful selection of the measurement points we believe to be able to get to the fault gaps of the intensely deformed fault zone and with used construction of monitored sites in a trench we will bridge thus about 4 m from the main fault plane, like in the site H3. In that we can count with the fact that massive blocks will incorporate effects of a wider zone. From this point of view we obtain data just along the main fault plane discontinuity which have to be only a fraction of the bulk. What the fraction could be? The estimate should be individual regarding the situation. However, according to our estimate while using the trench monitoring system it should be between 50 and 80 per cent of the effect of the full width of the fault zone. This is then what means the amount given as the monitored value in the points H3, L1, and TR1 where the trench system has been used. Other points have been installed on minor joints and cracks, and they would show minor reactions therefore. Yet, there is an experience that the general behavior in time regarding trends and accelerations even of minor cracks can be well informative.

There are three points of our network near Aigion that provide basic results. The points are H3, L1, and TR1. Other points may provide additional information. E.g the point H2 is in the area of H3 and belongs evidently to the same section of the Heliki fault zone but represents a minor joint. Monitored trends are of the same sense then but in H2 by one order lower than in H3 (Fig. 7).

Average long-term trends observed as well as reactions to a local earthquake with M = 4.8 of June 1, 2003 are given in Tables 1 and 2. The said earthquake was well felt early in the night of June 1, 2003 by the authors present just that time in the region of Aigion personally. All the points were registered before and shortly after the earthquake.

Principal observations (Table 1) can be summarized as follows.

1. General uplifting trend of the southern massif above southern coastline of the Gulf of Corinth has been confirmed. It has been evidenced as the main phenomenon at both the points H3, and L1,

**Table 1** Long-term trends and local earthquake reactions in displacements.

| **Fault** | Point | Long-term trends [mm/year] | | | | | | Earthquake reaction [mm/duration in month] | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Vertical z +uplift of the Southern block | | Lateral y + left lateral | | Transversal x + joint closing | | Vertical z +uplift of the Southern block | | Lateral y + left lateral | | Transversal x + joint closing | |
| | | before q | after q | before q | after q | before q | after q | before q | after q | before q | after q | before q | after q |
| Heliki | H2 | +0.06 | +0.06 | +0.60 | +0.60 | -0.04 | -0.04 | 0 | 0 | -0.03/1 | +0.08/2 | **S-0.14/1** | **S+0.21/2** |
| | H3 | +0.50 | +0.50 | 0.0 | 0.0 | -0.29 | -0.29 | 0 | **+0.7/1** | 0 | +0.3/1 | 0 | -1.1/1 |
| | H5 | -0.032 | -0.032 | -0.042 | -0.042 | -0.038 | -0.038 | X | X | X | X | X | X |
| | L1 | +0.0 | +9.14 | +10.0 | +6.29 | +0.0 | -8.00 | **S+5.0/4** | 0 | **S+7.0/4** | +2.0/1 | -16.0/4 | -4.5/1 |
| Aigion | A1 | -0.22 | -0.22 | -0.30 | -0.30 | -0.94 | -0.94 | X | X | X | X | X | X |
| | A2 | +0.185 | +0.0 | +0.023 | +0.023 | -0.06 | -0.06 | X | -0.11/3 | X | X | X | X |
| Trizonia | TR1 | **-8.05** | **+0.69** | +1.05 | +1.05 | -0.3 | -0.3 | 0 | +4.0 | 0 | 0 | 0 | 0 |

Bold letters – prominent change ; 0 – neutral; X – no observation ; **S -** S-like movement;

q – local earthquake of June 1. 2003; M = 4.8

**Table 2** Long-term trends and local earthquake reactions in angular deviations.

| **Fault** | Point | Long-term trends [π/200/year] | | | | Earthquake reaction [π/200/ duration in month] | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Vertical xz | | Lateral xy | | Vertical xz | | Lateral xy | |
| | | +opening upwards | | +opening to SE | | +opening upwards | | +opening to SE | |
| | | before q | after q | before q | after q | before q | after q | before q | after q |
| **Heliki** | H2 | +0.012 | +0.012 | 0 | 0 | 0 | 0 | 0 | 0 |
| | H3 | -0.03 | -0.03 | -0.03 | -0.03 | 0 | 0 | 0 | **+0.13/1** |
| | H5 | +0.0 | +0.0 | -0.016 | -0.016 | X | X | X | X |
| | L1 | -0.860 | +0.0 | **+0.0** | **+3.66** | **-0.8/3** | **S+1.4/2** | **S+0.5/4** | -0.0/4 |
| **Aigion** | A1 | 0 | 0 | 0 | 0 | X | X | X | X |
| | A2 | +0.021 | +0.021 | 0 | 0 | X | X | X | X |
| **Trizonia** | TR1 | 0 | 0 | 0 | 0 | **+1.8/3** | **+1.8/3** | +0 | **+0.4/1** |

Bold letters – prominent change; 0 – neutral; X – no observation;
**S -** S-like movement; q – local earthquake of June 1. 2003; M = 4.8

where after 31 months of observation, the uplift reads totally 1.95 *mm* and 34.5 *mm*, respectively. As for the micro-movements, the uplifting trend has been observed also at H2.

It is important to note that the uplift was evidenced at relatively distant points (H3 / L1) of the fault. Therefore, the effect is of a regional tectonic character.

2. One order higher movement rates at L1 than at H3 will correspond with a fact that the massif of Lakka is currently recorded as a place of micro-seismic tremors. The massif moves as a huge individual block in skew uplift above the valley, which corresponds with its form in the terrain morphology.
3. The said local earthquake was found to interfere in the micro-movement trends. However, reactions were not immediate, they were rather occurring in a period of one to two months as after-effects. Typical effects like this were observed at H2 and H3. Besides, precursor effects were observed also. A typical one occurred at x coordinate of H2. It represented opening of the joint at the end of the spring period when, regarding rock dilatations due to temperature increase, joints have a tendency to close. This precursor joint opening represented about 50 per cent unexpected return in the amplitude of seasonal joint dilatation.
4. In the period before and after the earthquake, L1 movements did not exemplify any sudden change but a slow S-like development of acceleration that passed to deceleration or even backing after the quake and later return to standard trends. The form of the curve recalls stress diagrams of rupture tests in rock mechanics when stress increases with deformation uniformly then slows down due to plastic deformation and after reaching the ultimate value comes down to a residual where rupture takes place. This may suggest that fault deformation deviated from the standard slipping trend of an aseismic creep to follow internal *stress concentration growth* leading to the instability in the focus and a quake, later restrained and came back to standard creep again.

   Even other points showed some S-like movements in that period, but not so clearly developed as L1 did.
5. Points H5, A2, A1 seem to provide less effective results. It is partially due to their positioning on artificial structures, partially due to a situation of being placed in the region of the sedimentary fan of the Selinoundas River where tectonic movements will be interfered with increasing superficial load and flood effects. There are quite strong seasonal effects in their data. It is believed that even these points will come to provide more intelligible data but need longer period of monitoring. It is our experience that in case of strong seasonal variations monitoring should cover longer periods than three years for the seasonal interference to be better understood before detailed interpretation of results.
6. Point TR1 shows extreme climatic effects and also quite high reactions in the period of the local earthquake. It suffered an abrupt change of vertical movement (Table 1) at that time, as well as an abrupt angular turn (Table 2). However, the point needs longer monitoring to provide data better intelligible. Available structural profiles of the Gulf and the island show a more complex graben/horst structure near the northern shore, while the measurement point is set on a structure conformal in orientation with that of the south shore faults. It is believed that the point was well situated, however more points will be needed on the northern shore to analyze the situation.

7. Angular deviations are provided by the TM71 gauging also. Results are given in Table 2 and the numbers indicate relatively very low values. This is supplementary information of sensitive reaction to stress changes and any interpretation as to possible generalized field movements calls for more complex reasoning with careful regard to local conditions.

Analysing the situation of individual monitoring points we can observe that it is just the point H3 that indicate a slow increase in $p$ component of displacements (Fig. 4). This is an important indication of a progressive compression in the point and therefore also of a real uplift in the area contrary to a possible gravitational down-slipping of the forefield that might be at least partially considered responsible for the observed shear ($s$ component in Fig. 4) along the investigated discontinuity. This means really that local conditions at the point H3 cannot be blamed from any possible landsliding that would interfere with the results at this point. (This is contrary to point L1 where $p$ indicates progressive extension, therefore one might assume that the indicated vertical movements are partially due to gravitational forefield slips, which exaggerate to a degree the uplift that was found extreme here.)

Therefore, our interpretation comes to accept point H3 found in compressive state as most representative even in case of angular deviations. Angular deviations at H3 are exposed in Fig. 5. The graph shows clearly that $\gamma_{xy}$ - deviations in the horizontal plane *xy,* develop slowly to negative values being interrupted here with two major episodal positive return steps. One episode like that coinsides with the earthquake of June 1, 2003. What does it mean? Negative trend means here systematic *westward angular opening*, i.e. westward extensions that are episodically interrupted with reversal effects. The interpretation then comes to a result that the systematic negative trend indicated a tendency for westward opening in the Gulf. An episode like the earthquake is manifested by a dynamic mass movement triggering an incremental gravitational slip registered as an incremental reverse rotation.

Resulting interpretation then supports the hypothesis of a long-time westward opening in the Gulf. We may add that a similar process of step-like negative development in $\gamma_{xy}$ including the earthquake effect was registered at the point TR1 located at the opposite northern shore of the Gulf.

## CONCLUSIONS

3D micro-movement monitoring registered vertical shifts as the main deformation process along Heliki/Lakka fault that confirms general uplifting of the southern massif. The movement is combined with left-lateral movements and extension in the fault. This is in accord with a view upon the Gulf of Corinth as of a graben in active formation. Moreover, horizontal rotation of monitored blocks corresponding to a systematic westwards opening of the Gulf was observed

Registered movement data in several monitoring points provided precursors and after-effects of the local earthquake. Such effects were registered in a period of up to four months before and three months after the earthquake. The character of such effects shows they are due to stress/strain development leading to instability and quake in the massif, and thereafter to restrain and return to standard aseismic creep.

Monitoring applied successfully 3D crack gauges working on the principal of mechanical interference between optical grids, a system of high long-term stability under severe outdoor conditions.

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