Vertical Movements in the Carmal Mountain

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SUMMARY

Researches from recent years have implied a horizontal movement neighboring the Carmel Fault. In some of those researches, it has been suggested that in addition to the horizontal movements, vertical deformations occur in the vicinity of the fault, as well. Results from geo-dynamic measurements over the recent 14 years show that the Carmel Mountain is rising at a rate of 5 mm per year with regard to its geographical surroundings. The research has been based on the use of two independent methods: precise leveling and GPS measurements.

The continuance of the monitoring, which partial results are published in this paper, focuses upon evaluating the vertical movements, probably they are the major movements taking place. The monitoring includes precise leveling, over 30 km in length, initiating at the Carmel coastal plane, crosses through Mount Carmel and proceeds towards additional mountainous structures, Tiv'on Hills and the Lower Galilee, that will serve as a comparable basis.

From 1986 onwards, at least two leveling processes have occurred between every 2 sequential benchmarks. The comparison results between the present campaign and its previous ones indicate differences in the altitudes differentials between the different lines. Mathematical calculations, including the use of least squares method, imply the existence of differences in altitude differentials among the different lines and also enable the calculation of the velocity of changes among the altitudes' differentials between any two sequential points and the velocity of changes with regard to time (acceleration), when there are more than two measurements per line.

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1. GENERAL BACKGROUND

The Syrian-African Fault constitutes a fault-line between the Arabian plate and the African plate. In Israel, it passes through the Jordan Valley and the Arava and continues south along the Red Sea and north to the Lebanon Valley. The fault extends many arms of sub-fault systems towards the two plates it bounds. The northern part of Israel is enriched with theses type of arms that take part in the design of the geological and geo-morphological landscape.

One of the most important and tectonically active amongst these systems is the Carmel-Tirza faults system (figure 1). This system consists of many different faults, and its general direction is southeastern and northwestern. The research focuses upon its northwestern part, at the Carmel Fault.

The Carmel Fault constitutes one of the most important structural elements in the geology of Israel. researches show that it is seismologically active, a fact that brings about deformations in its surroundings, and establish their results on geological research tools. The geographical areas existing northeastern and southwestern of the fault are completely different in their topography, structure, the seismological activity occurring within them, in the deep membrane's structure within their boundaries and additional geological characteristics. The deformations in the vicinity of the fault that are directly derived from the membrane's characteristics in each defined area are not uniform.

The geological research is at a division of opinions with regard to the movement directions of both sides of the fault. Whereas there is an agreement regarding the existence of a sliding motion, which brings about horizontal deformations, there are two approaches regarding the issue of whether there is also a collision (compression) between the two sides of the fault. One of the approaches claims that such a movement exists and it is concentrated in the central part of the movement, in the area which direction is north-southern. The compression movement brings about the subverting of the eastern side from under the western side and causes a relative rise of the western side (Achmon, 1997. Glick, 2001).

2. GPS MEASUREMENTS

The geodetic monitoring began at the end of the 80s. At its commencement, the Carmel network was established, including 17 points. Approximately half of them were located on the Carmel Mountain and the others were located at Menashe Heights, Tiv'on Hills and southwestern part of the Lower Galilee, from the northeastern part of the fault. This monitoring included two sequential measurements made at a time difference of approximately 8 months apart. These measurements were integrated, for the first time, in a geophysical research in Israel, the GPS technology. This technology provided an additional aspect and enhances the reliability level of deformations monitoring. Carrying out this innovative action, with no prior experience, a small number of GPS satellites in space, at that time, and the use of single-frequency receivers have impaired the quality of the first measurements campaign (1990). In the second campaign (1991), the technique was refined, but the objective conditions remained harsh, having some of them even worsen. The research's results have shown that regarding some of the points, the horizontal components have shifted in a substantial manner, compared to the reference point, but due to the short range of time between them, theses results have remained reserved and both monitoring were combined into one (Even-Tzur, 1991).

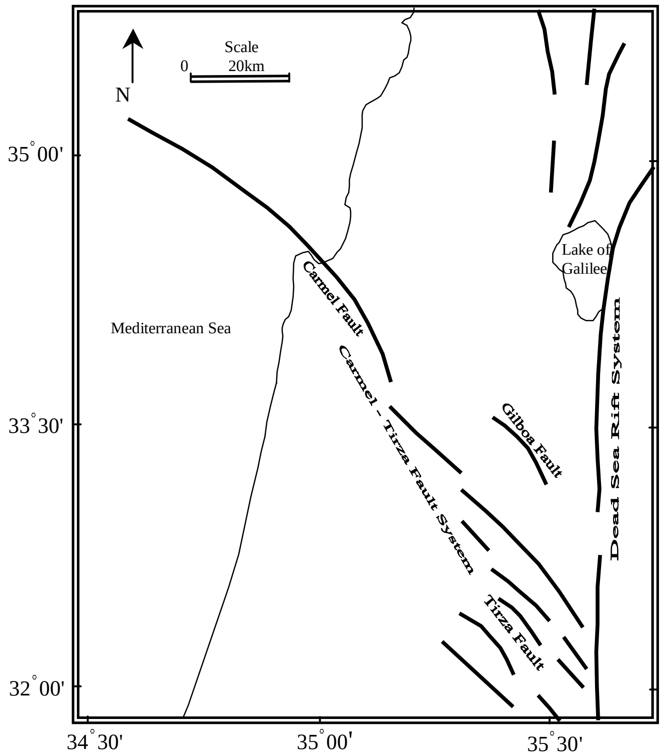

Figure 1: The Carmel-Tirza fault system and the Dead Sea Rift in north of Israel-solid lines represent faults (Hofstetter, Van Eak and Shapira, 1996)

In 1994, as part of the Undulation Project, the Survey of Israel (SOI) has carried out an additional measurements campaign. The measurements accuracy, which had not been designated for geo-dynamic purposes, was lower than that required for examining the Carmel network, but its significance lies in the fact that for the first time ever, there has been use of double-frequency receivers, the number of vectors measured has brought about a large excess of observations, and most important, that no additional campaign has been carried out up to 1999, excluding two local measurements that included a limited number of points on the network.

In 1999, an additional measurement of the network was made, during which the lessons of the previous campaign had been applied. This measurement was made with an improved GPS infrastructure and through the use of double-frequency receivers, which included P-code. This campaign has significantly showed a relative rise of the Carmel ridge at a rate of 4-5 mm a year compared to its geographical surroundings (Agmon, 2001).

In the 90s - the G1 Network was established- the geodetic-geodynamic network of Israel. Up to date, two cycles of measurements had been made, in 1996 and in 2002. These days, these measurements are processed, within the research framework, with the use of scientific software for processing vectors in order to examine the deformations which had occurred during these years.

3. PRECISE LEVELING

A leveling line included 31 benchmarks across a route that cuts through the Carmel Mountain from Atlit up to Nesher, approximately 20 km long (see figure 3), was measured between May 1987 and December 1992. The leveling line has been measured by SOI according to the criteria of International Association for Geodesy.

In four sections of this line, additional leveling have been made, independent of the two central measurements. The analysis was made with the use of data which had been extracted from the archive of SOI. Precise leveling is a more accurate method for evaluating the vertical deformations than GPS measurements. The sections which had been leveled twice, in a simple manner of the difference of the altitude differentials between the two leveling with regard to the time difference, in which they were made. In order to examine sections leveled more than twice, there has been use of mathematical tools for adjusting surpluses observations. The results of the precise leveling have strengthened the results of the GPS measurements that have indicated a rise of the Carmel with regard to its surroundings at a rate of approximately 5 mm a year (Even-Tzur, 2003). The Mount Carmel range, considered to be stable, vertical-movement wise, has been chosen to serve as a datum, with which regarding to, the deformations of the points in its surrounding slopes have been measured, the steep northeastern and the moderate south-western.

The long time which had passed since the carrying out of the last leveling has created the need to implement an additional leveling campaign. In order to make the monitoring more efficient and expanding the possibilities of deducting regarding the vertical behavior of the Carmel Mountain, it has been agreed to prolong the leveling line and through it, relate the Carmel Mountain to additional geographical structures, Tiv'on Hills and the Western Galilee. The continuance of the monitoring includes a precise leveling campaign at a length of more than 30 km that commences in the plane of the Carmel coast, passes through the Mount Carmel, and continues towards two additional mountainous structures, Tiv'on Hills and the Lower Western Galilee. Together with the expanding of the network, it has been decided to dense it and add 7 new benchmarks at the western part, which had been characterized by development works which had destroyed some of the points. This dense making does not assist this stage of the research, but can be of great assistance in its continuance, in the future.

The leveling line that connects the Carmel with these structures is carried out these days and processing their results will enable to examine the Carmel's movement with relation to them. For the purpose of calculations, there will be use of a leveling line from 1986 that goes through some of the points that are currently measured.

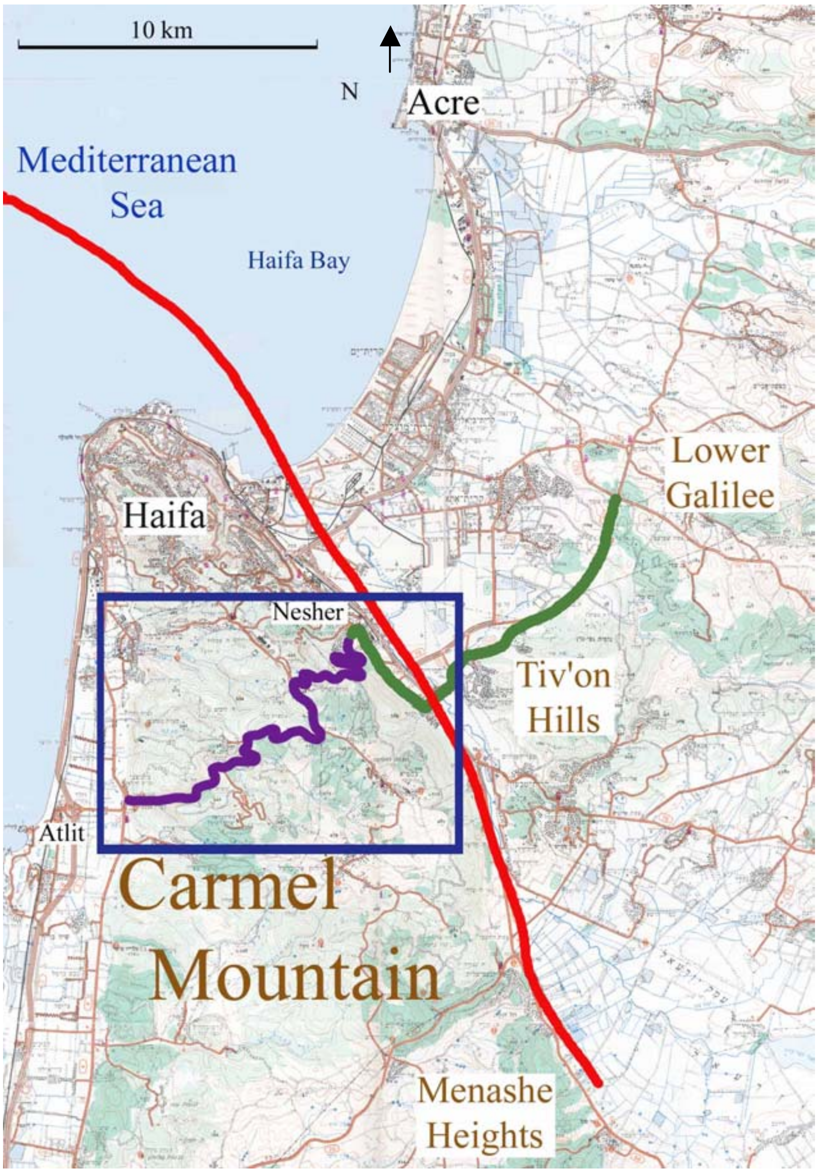

Figure 2: Carmel Mountain and its surroundings' map.
Red line - the Carmel Fault. Purple line – the leveling line.
Green line – the extension of the leveling line.
The area inside the blue rectangle is enlarged scale in Figure 3

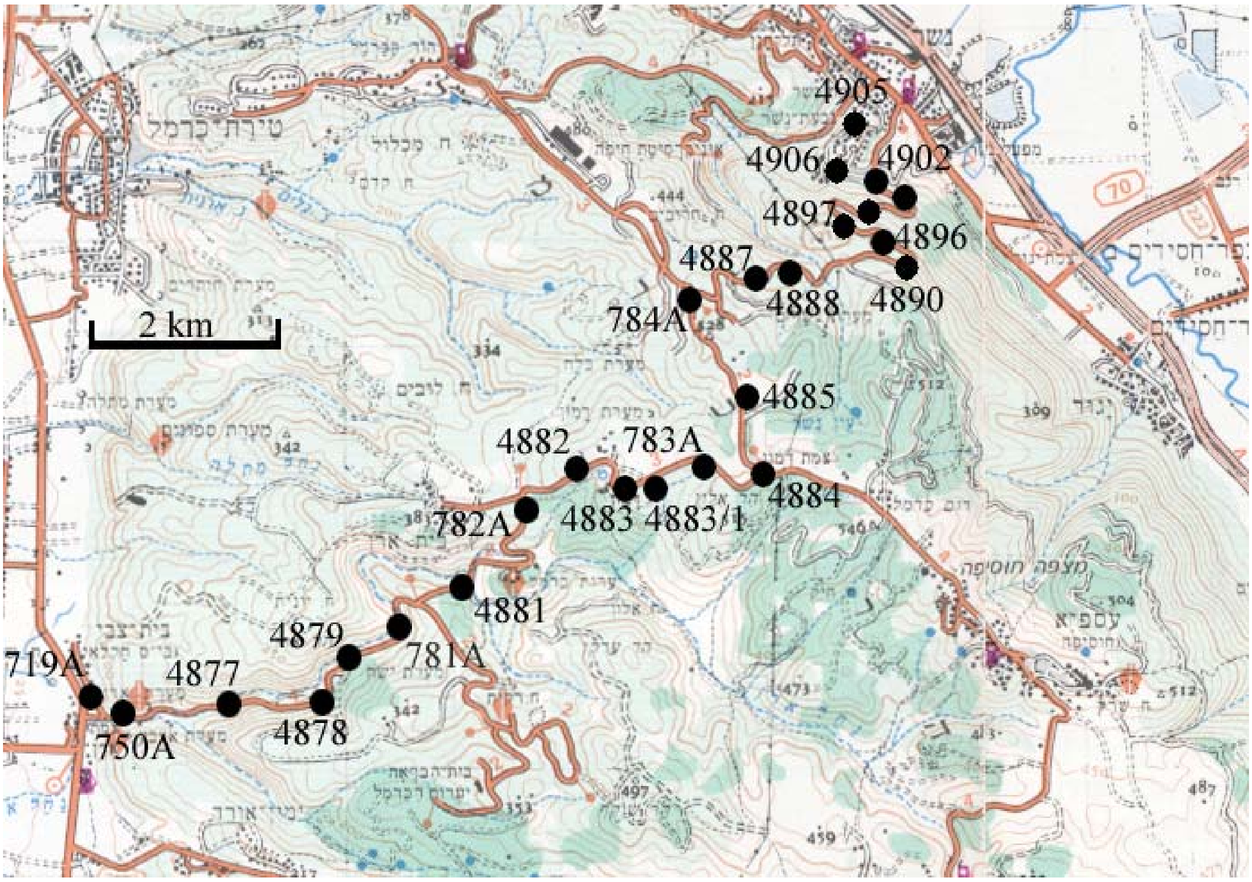

Figure 3: Map of the leveling lines from Atlit (719A) to Nesher (4905) with the location of 23 benchmarks

4. DATA PROCESSING

Due to the wide dispersal of measurements in the space of time and the inability to boarder them in defined sets of time, which time difference between their end and beginning isn't negligible, we decided to make use of the kinematic linear modal for the calculation of the movement velocity between two adjacent points:

$$x_i = x_0 + \dot{x}(t_i - t_0) \qquad (1)$$

Where x_i is the altitudes vector at a given time t_i. The reference altitudes vector is x_0, the reference time is t_0 and the points' velocities vector is $\dot{x}$.

In fact, together with the measurements cycle in the years 2003-2004, it is possible to use the quadratic model which also calculates the acceleration:

$$x_i = x_0 + \dot{x}(t_i - t_0) + \frac{\ddot{x}}{2}(t_i - t_0)^2 \qquad (2)$$

While $\ddot{x}$ is the accelerations vector that is solved for every line that has been leveled at least 3 times. Most of the leveling sections in this monitoring have been measured only 3 times, hence the solution of the acceleration has no degree of freedom at all, or only one degree of freedom, and the results of the acceleration must be, at this stage, reserved, and used only to obtain a general snap shot.
In order to examine the coordinated velocities of the movement of the altitudes' differences on the time axis, we use the linear coordination model (Koch):

$$\begin{bmatrix} L_1 \\ L_2 \\ \vdots \\ \vdots \\ L_k \end{bmatrix} - \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ \vdots \\ V_k \end{bmatrix} = \begin{bmatrix} A_1 & 0 & 0 & \cdots & 0 \\ 0 & A_2 & 0 & & 0 \\ \vdots & & \ddots & & \vdots \\ 0 & 0 & & \ddots & 0 \\ 0 & 0 & 0 & \cdots & A_k \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ \vdots \\ X_k \end{bmatrix} \tag{3}$$

Where L_i and V_i are the observations and residuals vectors of leveling line number i, A_i is the coefficient matrix of the unknown parameters. The unknown parameters contained in every sub-solution vector:

$$X_i^T = \begin{bmatrix} x_{0i} & \dot{x}_i & \ddot{x}_i \end{bmatrix} \tag{4}$$

Where k is the number of the leveling line.
The covariance matrix of the unknown parameters is calculated in the following manner:

$$\Sigma_{\dot{x}_i} = \sigma_0^2 \begin{bmatrix} Q_{11} & 0 & 0 & \cdots & 0 \\ 0 & Q_{22} & & & 0 \\ \vdots & & \ddots & & \vdots \\ 0 & 0 & & \ddots & 0 \\ 0 & 0 & 0 & \cdots & Q_{kk} \end{bmatrix} \tag{5}$$

Q_{ii} is the cofactor matrix for leveling-line i. We set $\sigma_0^2 = 1$ in order to maintain the reality of the solution's accuracy.

5. CHOOSING THE DATUM POINTS

The choosing of the datum points involves a few considerations. First of all, the chosen group of points has to be on the ground which is geologically found to be stable and homogeneous. Second, the group of points must satisfy the null hypothesis:

$$H_0 : \dot{x}_1 = \dot{x}_2 = ... = \dot{x}_r = 0 \tag{6}$$

While aside this:

$H_1 : \dot{x}_1 \neq 0 \,\|\, \dot{x}_2 \neq 0 \,\|\, ... \,\|\, \dot{x}_r \neq 0$

While r is the number of the lines between the benchmarks that have been chosen to serve as a Datum.
We will reject H_0 with a confidence level of $1-\alpha$ if

$$\frac{|\dot{x}_1|}{\sigma_1} > Z_{1-\frac{\alpha}{2}} \,\|\, \frac{|\dot{x}_2|}{\sigma_2} > Z_{1-\frac{\alpha}{2}} \,\|........\|\, \frac{|\dot{x}_k|}{\sigma_k} > Z_{1-\frac{\alpha}{2}} \qquad (7)$$

The meaning of accepting the null hypothesis H_0 is that the datum points are stable with regard to themselves at a significance level of α.
In the first stage an arbitrary reference benchmark defined as a temporary datum, according to which the velocities and accelerations of the other points will be determined. We must now perform a transformation between the temporary datum and the datum chosen in the following manner:
Helmert matrix for the datum defect $d = 1$ will be a column vector at the size of k:

$$H^T = \begin{bmatrix} 1 & 1 & \cdots & \cdots & 1 \end{bmatrix} \qquad (8)$$

The weights matrix P_X will be a matrix of zeroes, excluding elements of the diagonal that relate to the benchmarks chosen to serve as a datum and will be assigned the value 1.
The Jacobian matrix will be calculated in the following manner:

$$J = I - H\left(H^T P_X H\right)^{-1} H^T P_X \qquad (9)$$

And the solution of the velocities and accelerations according to the chosen datum will be:

$$\dot{X}_{new\_datum} = J\dot{X}$$
$$\ddot{X}_{new\_datum} = J\ddot{X} \qquad (10)$$

And their covariance matrixes will be calculated:

$$\Sigma_{\dot{X}_{new\_datum}} = J\Sigma_{\dot{X}} J^T$$
$$\Sigma_{\ddot{X}_{new\_datum}} = J\Sigma_{\ddot{X}} J^T \qquad (11)$$

6. RESULTS

The benchmarks chosen to serve as a datum are 4884, 4885 and 784A, and all three are situated on the Carmel's watershed. They were found to be highly stable at all time-sections examined.

Despite the reservation from the above mentioned solution of the accelerations vector, it can be seen that with regard to its elements, we reject the hypothesis that $H_0 : \ddot{x}_i = 0$ at a significant level of 5%. We can also see that the acceleration, when it exists, behaves according to the spatial location of the point. It is seen that at western slopes, the acceleration is negative and significant with regard to the ridge while at the eastern slopes, it is moderate and positive. This systematic behavior of the acceleration vector teaches us about systematic changes of the velocity vector. In order to examine this thoroughly without relying on the problematic solution of the acceleration, we have chosen, alongside with the simultaneous solution, to carry out time intersects and to independently examine the velocity vector at two different periods. The results indicate different velocities at the two periods.

model	**linear modal**						**quadratic modal**			
period	**1987-1992**		**1991-2003**		**1987-2003**		**1987-2003**			
point	**velocity**	$1.96\sigma_{\dot{x}}$	**velocity**	$1.96\sigma_{\dot{x}}$	**velocity**	$1.96\sigma_{\dot{x}}$	**velocity**	$1.96\sigma_{\dot{x}}$	**acceleration**	$1.96\sigma_{\ddot{x}}$
750A	**-5.623**	1.161	**1.290**	0.462	-0.188	0.354	**-7.649**	1.555	**0.886**	0.182
4877					-0.248	0.336				
4878	**-4.833**	1.071	**1.244**	0.428	-0.110	0.313	**-6.630**	1.436	**0.780**	0.168
4879	**-4.815**	1.033	**1.227**	0.417	-0.120	0.304	**-6.602**	1.388	**0.776**	0.162
781A	**-4.339**	0.975	**1.107**	0.396	-0.114	0.288	**-5.963**	1.311	**0.700**	0.153
4881	**-3.631**	0.849	**0.913**	0.351	-0.112	0.256	**-5.005**	1.146	**0.585**	0.134
782A	**-2.839**	0.744	**0.865**	0.313	0.021	0.229	**-3.982**	1.009	**0.478**	0.117
4882	**-1.649**	0.540	**0.607**	0.244	0.071	0.185	**-2.381**	0.741	**0.293**	0.086
4883	**-0.528**	0.484	**0.389**	0.219	0.141	0.166	**-0.852**	0.663	**0.119**	0.077
48831	-0.283	0.403	**0.208**	0.184	0.078	0.137	-0.443	0.555	0.064	0.064
783A	-0.171	0.308	**0.226**	0.143	**0.119**	0.099	-0.295	0.427	**0.051**	0.051
4884	-0.136	0.213	**0.107**	0.102	0.040	0.068	-0.212	0.296	0.031	0.036
4885	0.015	0.160	-0.030	0.074	-0.017	0.050	0.029	0.222	-0.006	0.027
784A	0.121	0.288	-0.077	0.132	-0.023	0.088	0.182	0.399	-0.025	0.048
4887	-0.221	0.558	-0.237	0.252	**-0.229**	0.176	-0.215	0.770	-0.002	0.091
4888	-0.552	0.600	**-0.275**	0.271	**-0.341**	0.189	-0.637	0.828	0.035	0.098
4890	**-1.034**	0.733			**-0.823**	0.462				
4897	**-0.870**	0.807	0.071	0.311	**-0.524**	0.474	-0.531	0.950	0.059	0.113
4900	**-1.286**	0.898	0.200	0.359	**-0.533**	0.491	-1.117	1.095	0.129	0.130
4902	**-1.538**	0.956			**-0.785**	0.590				
4906	**-1.404**	1.011			-0.651	0.676				
4905	**-1.201**	1.057	0.329	0.385	-0.503	0.683	-0.892	1.173	0.120	0.139

Table 1: The velocities (mm/year) and acceleration (mm/year^2) of the benchmarks relative to the Carmel Mountain range. The bold numbers denotes significant values

7. CONCLUSIONS

The monitoring has been based on 23 points that are scattered throughout the Carmel Mountain's breadth and basically includes three measuring cycles that has been measured during the recent 17 years with different time differences.

The simultaneous solution indicates stability of the western slopes relatively to the mountains exterior and moderate rising of the mountain's exterior at a rate under 1 mm per year compared to the eastern slopes.

Despite the importance of the simultaneous solution, it includes the loss of much valuable information, therefore solutions were arrived at with the use of two intersects on the time axis.

From the analysis of these solutions, it is seen that in the first period, the Carmel ridge has risen at a rate of up to 6 mm a year with regard to its western slopes and at a rate of approximately 2 mm a year compared to the eastern slopes. Analysis of the second period's results indicates that the ridge's center does not rise, and even sinks at a rate of 1 mm per year compared to the western slopes.

The calculations of the leveling measurements, carried out these days, run through the Carmel's Fault, northeastern towards Tiv'on Hills, and the Lower Galilee will enable to examine the behavior of the Carmel Mountain with regard to the other side of the fault, therefore assisting to understand the fault's behavior and trends.

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BIOGRAPHICAL NOTES

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