Surface Deformation along the Carmel-Gilboa Fault System by means of Extended Free Network Adjustment Constraints

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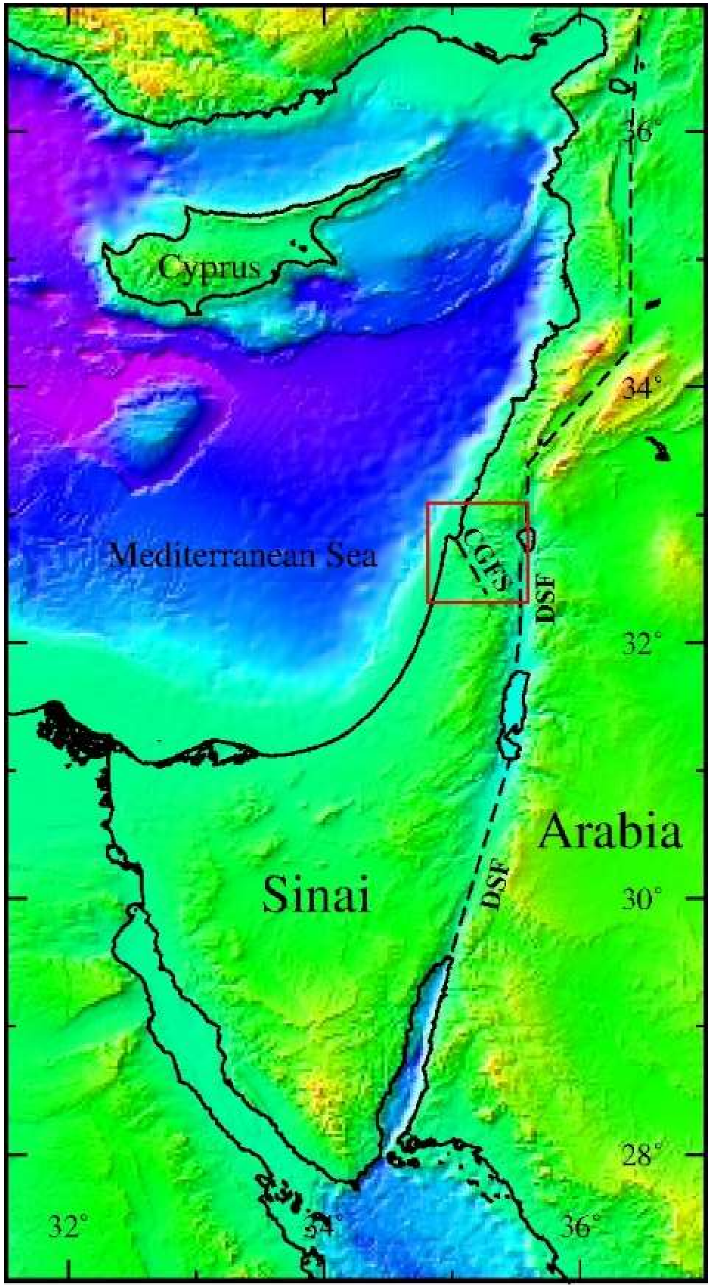
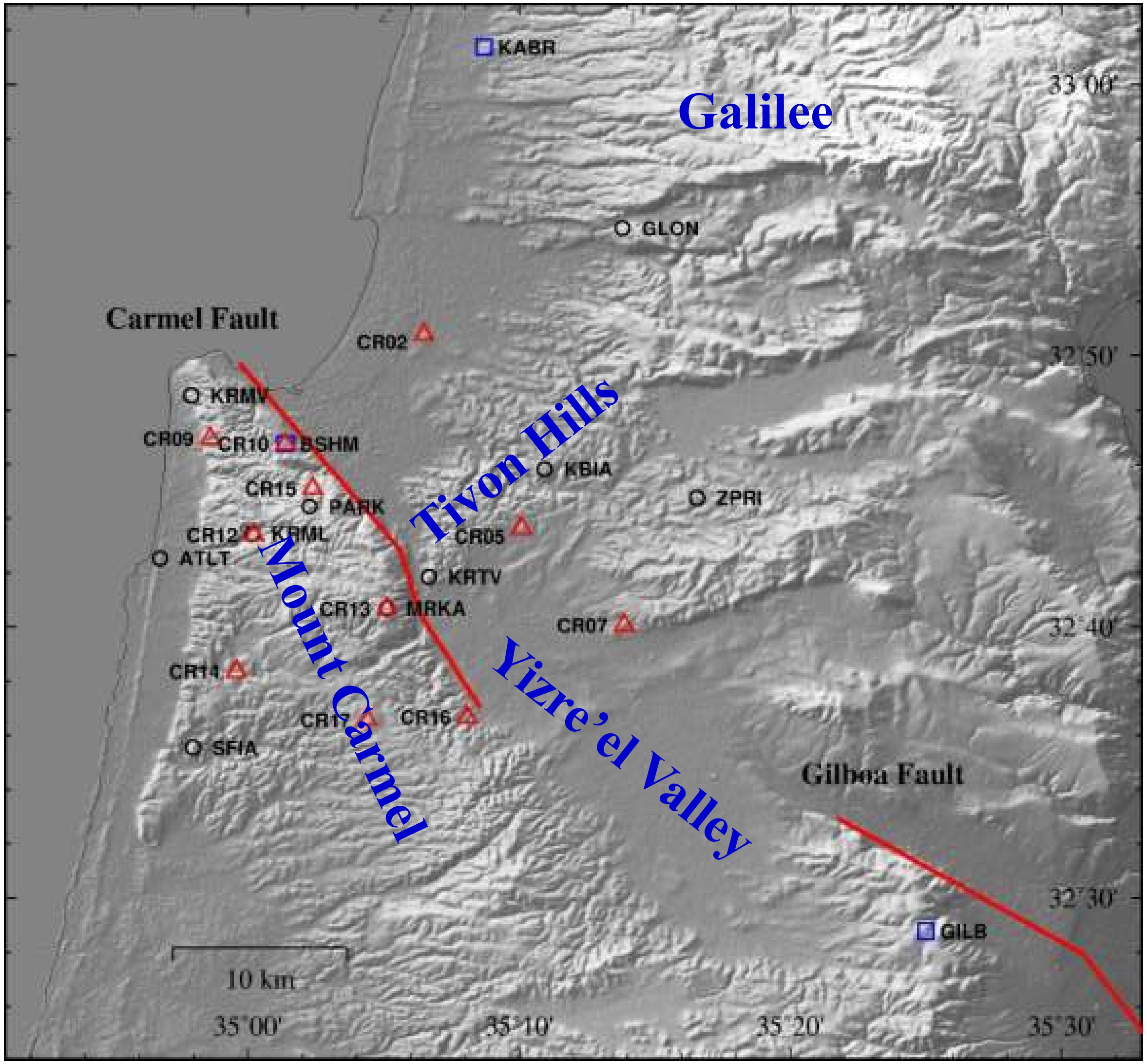
Geological Background

- ► The Carmel-Gilboa Fault System (CGFS) is one of the major geological structures of northern Israel.
- ► It is branch of the Dead Sea Fault.



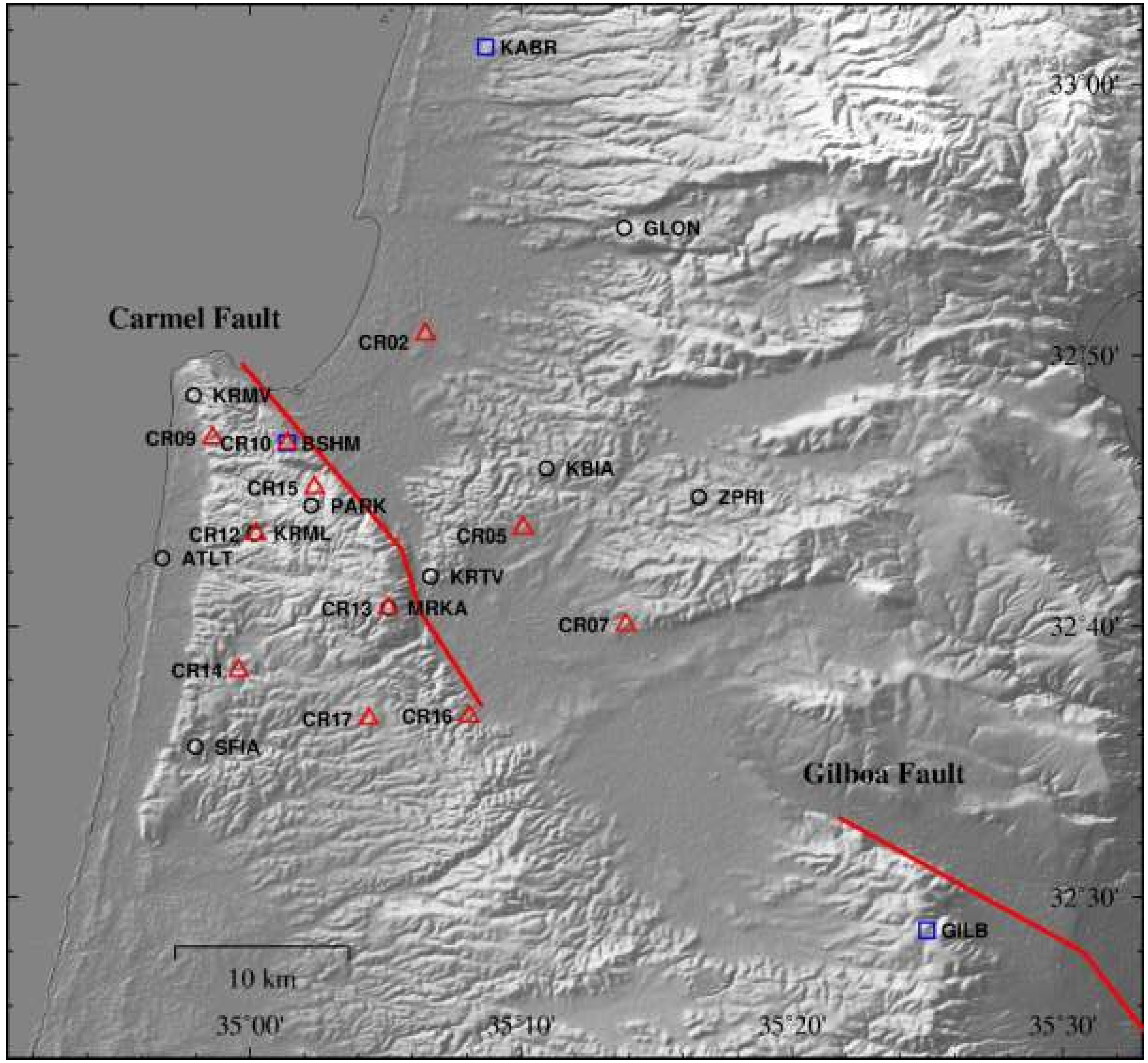
Geological Background



There is no agreement on the exact location of the CGFS.

GPS Network

The region is covered by monitoring geodetic network consists of 24 sites which were measured eight times between 1999 and 2016 by means of GPS.

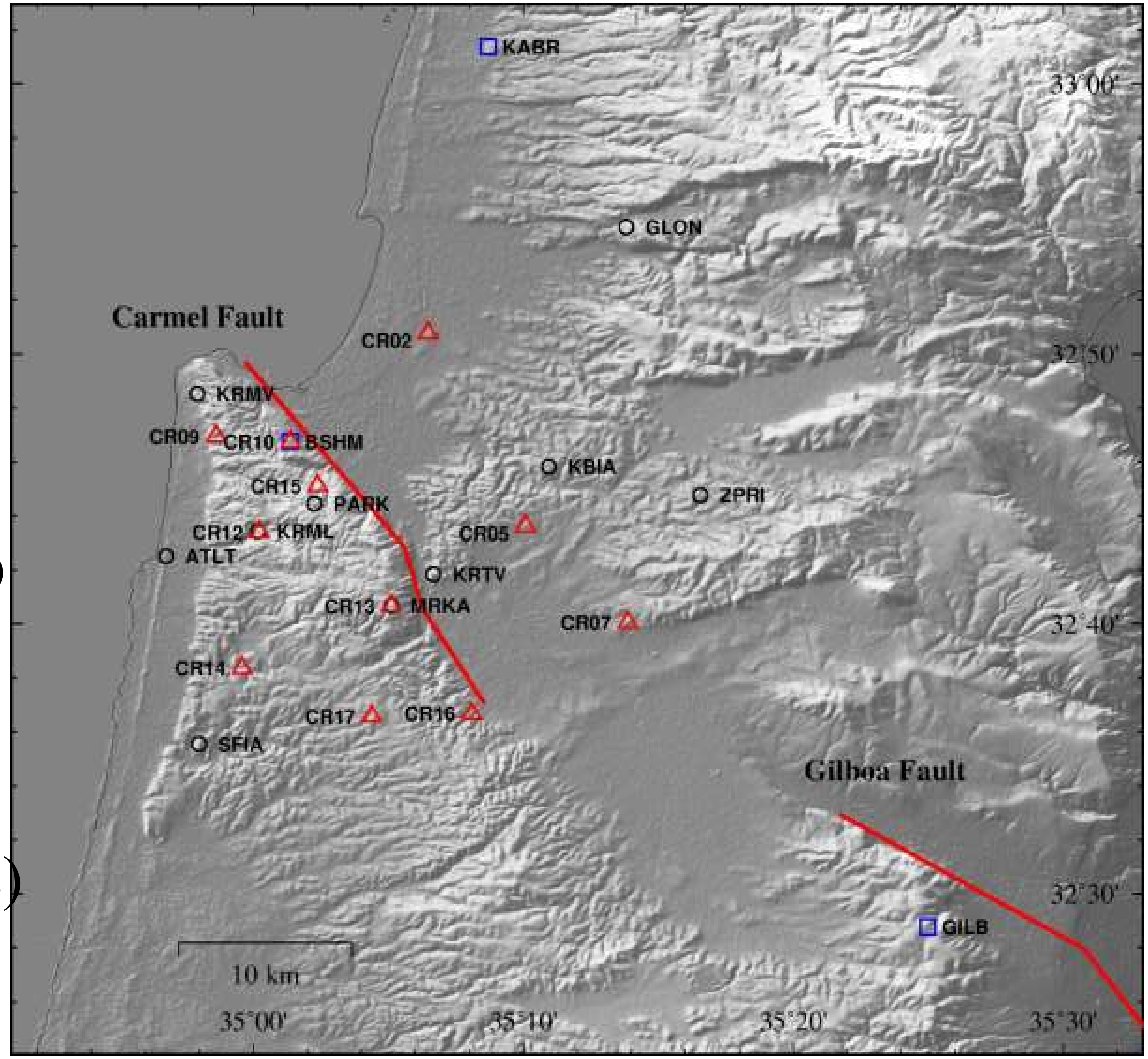


GPS Network

The GPS network consists of three parts that are combined in observation and analysis:

- ▲ Carmel Network (11)
- ● G1 Network (10)
- ■ APN Network (3)

(Israeli network of permanent GNSS stations)



Field Work

► All sites were occupied at least twice in each campaign.

► The observation time spans was 4 h for the 1999 campaign and 8 h for all the other campaigns (2006, 2009, 2010, 2011, 2012, 2014 and 2016).

► In 1999 and 2006 campaigns Choke Ring antennas were used along with geodetic antennas, since 2009 Choke Ring antennas were used exclusively.

► The Carmel network points were occupied using tripods.

► G1 network sites were measured using special centering devices, which allow an easier setup of the antenna.

GPS Data Analysis

► The GPS data analysis was done using the Bernese GPS Software Version 5.2.

►Data from seven APN sites and three IGS sites (NICO, ANKR and ZECK) are included in the GPS analysis.

► Precise ephemeris, EOPs and IGS coordinates from the weekly solution for IGS stations were used.

► Absolute phase centre variations with respect to IGS08 standard were used for all campaigns.

► The datum was defined by loose constraints of the IGS and APN site coordinates.

The Datum Problem

- ► The site velocities and deformation parameters can be estimable only if the datum of the network has not been changed between measurement epochs.
- ► GPS vectors can define the inner geometry of the points in the network, but they are incapable of completely determining its datum.
- ► GPS vectors in a network can define its datum parameter of **orientation** and **scale**.
- ► The remaining datum parameters are defined by imposing linear constraints on the estimated coordinate corrections.

The Datum Problem

- In GPS network the part of the datum definition determined by the vectors may not remain consistent.

- Fluctuations in the GPS orbits could affect the orientation and scale between monitoring campaigns, therefore we cannot assume that the part of the datum definition determined by the vectors is the same in each monitoring campaign and remains stable over time.

Proposed Solution

► The GPS vectors from each campaign are stripped from their datum content.

► The datumless measurements are used to define the datum by preliminary coordinates and linear constraints – *remain constant for all monitoring campaigns*.

► The datumless measurements are used to define the position of the network points and theirs velocities.

Extended Free Network Adjustment Constrains

Extended Free Net-Theoretical Background

Observation equations: ℓ $\quad\quad\quad\quad$ ν

The vector **w** is partitioned into global and local components through the introduction of a vector of parameters **y**.

y - the contribution of the measurements to the global component of the coordinates.

x - vector of sterilized coordinates.

The elements of **y** can be relate as the parameters of a transformation between two vectors **x** and **w**.

Therefore **w** can be presents as: $\mathbf{w} = \mathbf{D}\mathbf{x} + \mathbf{F}\mathbf{y}$

$\mathbf{D} = \partial\mathbf{w}/\partial\mathbf{x}$ is a u by u full rank matrix-deformation matrix.

$\mathbf{F} = \partial\mathbf{w}/\partial\mathbf{y}$ is a u by f full column rank matrix.

Extended Free Net-Theoretical Background

New observation equations:

$$\ell \qquad \mathbf{Dx}+\mathbf{Fy}) = \mathbf{C}(\mathbf{D},\mathbf{F})\begin{bmatrix}\mathbf{x}\\ \mathbf{y}\end{bmatrix} = (\mathbf{A},\mathbf{B})\begin{bmatrix}\mathbf{x}\\ \mathbf{y}\end{bmatrix}$$

When **D=I** and **F=0**, we have **x=w** and therefore:

$$\ell$$

the widespread model of a network adjustment

Extended Similarity Transformation

It is used to transform one solution, $\mathbf{x}$ and $\mathbf{y}$, pertaining to a certain datum, into another $\bar{\mathbf{x}}$ and $\bar{\mathbf{y}}$, pertaining to another datum.

The transformation is described by:

$$\bar{\mathbf{x}} = \mathbf{x} + \mathbf{D}^{-1}\mathbf{E}\mathbf{p} + \mathbf{R}\mathbf{q}$$
$$\bar{\mathbf{y}} = \mathbf{y} + \mathbf{q}$$

$\mathbf{E}$ - Helmert's transformation matrix.

$\mathbf{p}$ - vector of d datum transformation parameters.

$\mathbf{q}$ - vector of variations in the $\mathbf{y}$ parameters.

$\mathbf{R} = -\mathbf{D}^{-1}\mathbf{F}$ - u by f full column rank matrix, $\mathbf{R}$ represents an apparent functional relationship between $\mathbf{x}$ and $\mathbf{y}$.

For a unique solution of $\bar{\mathbf{x}}$ that yields $\bar{\mathbf{x}}^T\mathbf{P}_x\bar{\mathbf{x}} \rightarrow min$ it is required that $\partial(\bar{\mathbf{x}}^T\mathbf{P}_x\bar{\mathbf{x}})/\partial\mathbf{p} = 0$ and $\partial(\bar{\mathbf{x}}^T\mathbf{P}_x\bar{\mathbf{x}})/\partial\mathbf{q} = 0$

Extended Similarity Transformation

The transformation receives the form:

$$\bar{\mathbf{x}} = \left[\mathbf{I} - \begin{bmatrix} \mathbf{D}^{-1}\mathbf{E} & \mathbf{R} \end{bmatrix} \begin{bmatrix} \mathbf{E}^{\mathrm{T}}(\mathbf{D}^{-1})^{\mathrm{T}}\mathbf{P}_{\mathrm{x}}\mathbf{D}^{-1}\mathbf{E} & \mathbf{E}^{\mathrm{T}}(\mathbf{D}^{-1})^{\mathrm{T}}\mathbf{P}_{\mathrm{x}}\mathbf{R} \\ \mathbf{R}^{\mathbf{T}}\mathbf{P}_{\mathbf{x}}\mathbf{D}^{-1}\mathbf{E} & \mathbf{R}^{\mathbf{T}}\mathbf{P}_{\mathrm{x}}\mathbf{R} \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{E}^{\mathrm{T}}(\mathbf{D}^{-1})^{\mathrm{T}}\mathbf{P}_{\mathrm{x}} \\ \mathbf{R}^{\mathbf{T}}\mathbf{P}_{\mathbf{x}} \end{bmatrix} \right] \mathbf{x} = \mathbf{J}_{\mathrm{ex}}\mathbf{x}$$

$$\bar{\mathbf{Q}} = \mathbf{J}_{\mathrm{ex}}\mathbf{Q}\mathbf{J}_{\mathrm{ex}}^{\mathrm{T}}$$

Extended Free Net Adjustment and GPS

GPS vectors are used to determine the relative positions of the network points and the network datum parameters of **orientation** and **scale**.

Transformation of a single point from measured GPS coordinates, which contain the datum parameter, to coordinates which are stripped from their datum content is done by three rotations and a scale factor as follows:

$$\begin{pmatrix} x_w \\ y_w \\ z_w \end{pmatrix}_i = \begin{pmatrix} s & r_z & -r_y \\ -r_z & s & r_x \\ r_y & -r_x & s \end{pmatrix} \begin{pmatrix} x_x \\ y_x \\ z_x \end{pmatrix}_i = \mathbf{D} \begin{pmatrix} x_x \\ y_x \\ z_x \end{pmatrix}_i$$

Extended Free Net Adjustment and GPS

The transformation can also be presented in the following form:

$$\begin{pmatrix} x_w \\ y_w \\ z_w \end{pmatrix}_i = \begin{pmatrix} 0 & -z_x & y_x & x_x \\ z_x & 0 & -x_x & y_x \\ -y_x & x_x & 0 & z_x \end{pmatrix}_i \begin{pmatrix} r_x \\ r_y \\ r_z \\ s \end{pmatrix} = \mathbf{F}_i \mathbf{y}$$

Two Steps Deformation Analysis

► The estimation of velocity field was carried out by using the Two-Steps method.

First Step: Adjustment of each monitoring campaign to static independent network of points.

Second Step: The variation in network geometry is modeled.

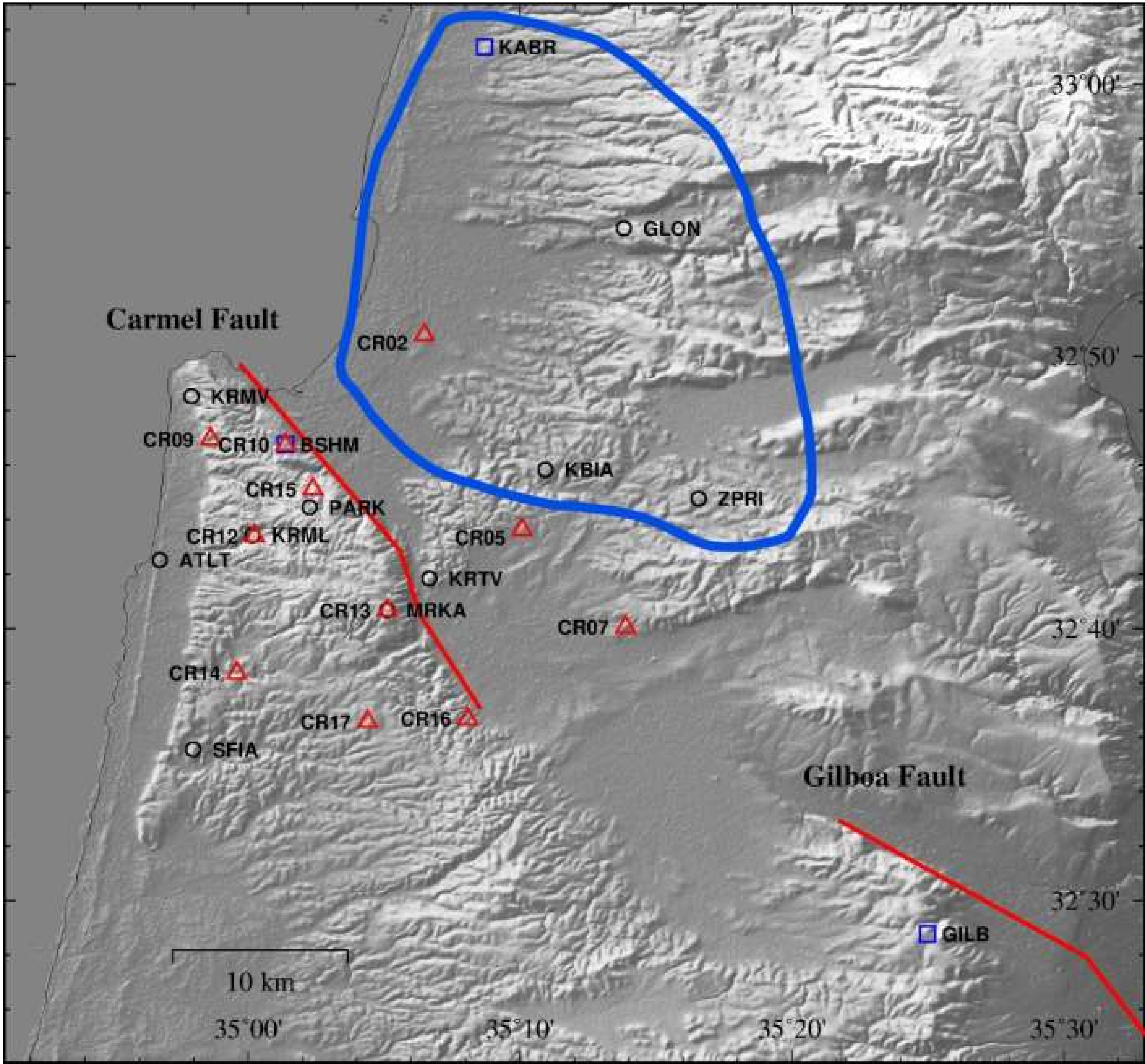
► Statistical tests are applied for estimating the correspondence of the motion model and its significance.

The Estimation of Velocity Field

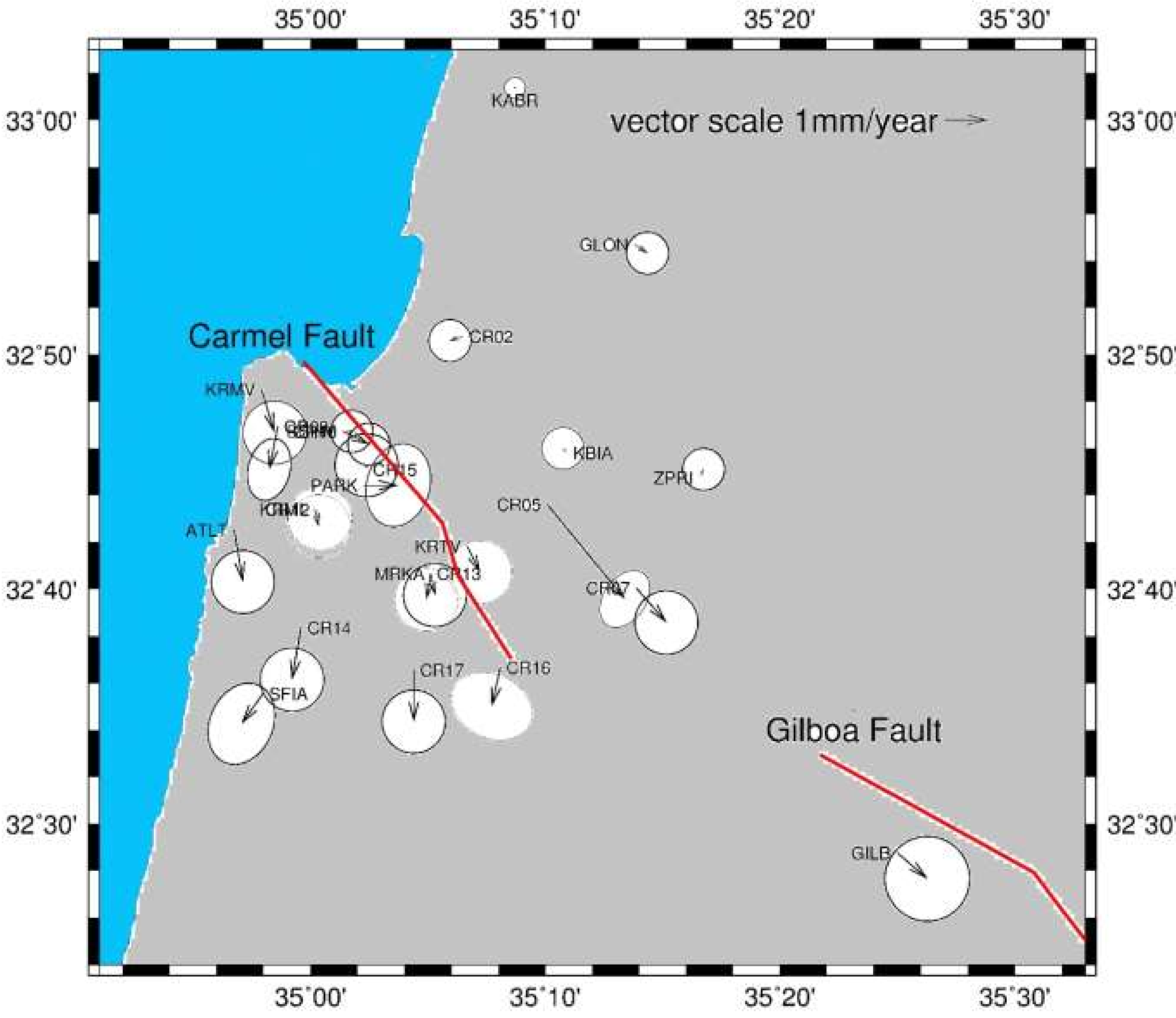
- ► The regional site velocities were estimated with respect to a local datum that was defined by a stable cluster of sites on one side of the fault by means of extended free net adjustment constraints and extended similarity transformation.
- ► The extended similarity transformation was applied to transform the velocity vector and its covariance matrix to a weight constrained solution.
- ► Congruency testing was performed to determine the stable datum points.

Stable Datum Points

5 stable points in the north part of the network were selected to define the datum.

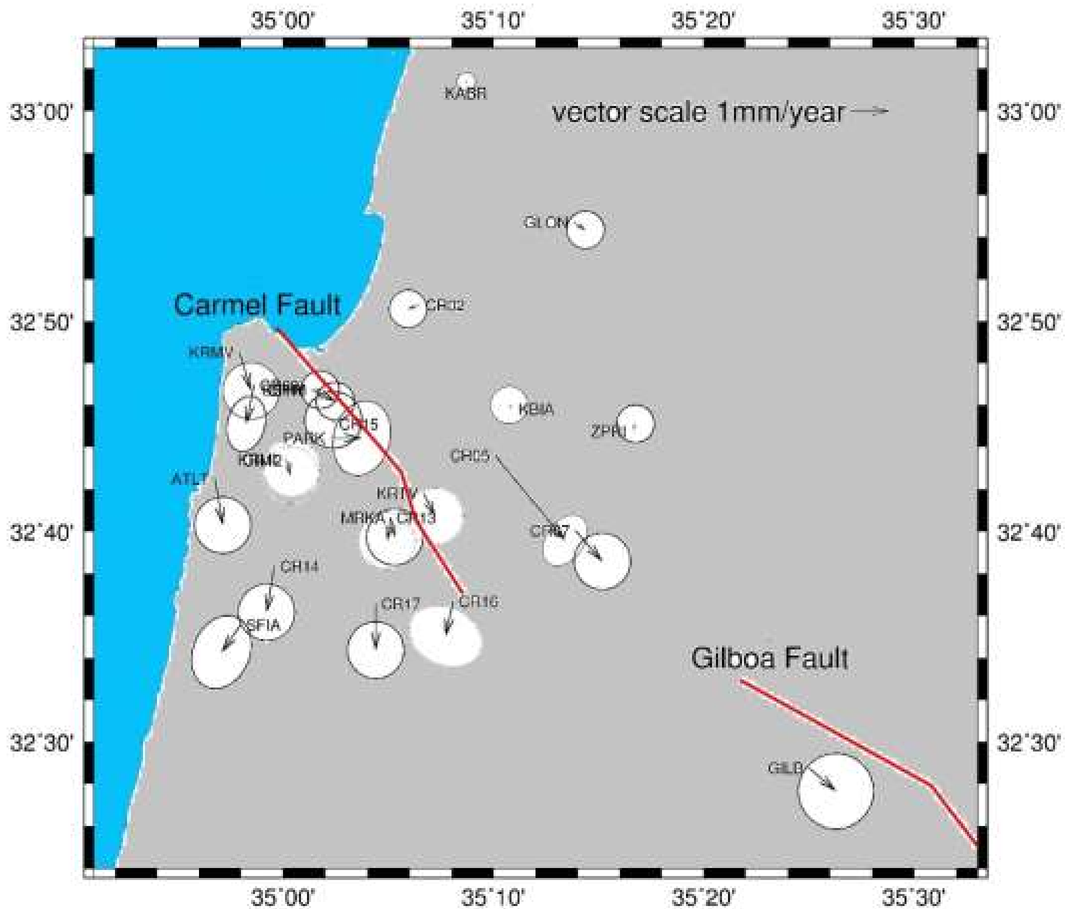


The Weight Extended Constraint Velocity Filed and their 95% confidence ellipses



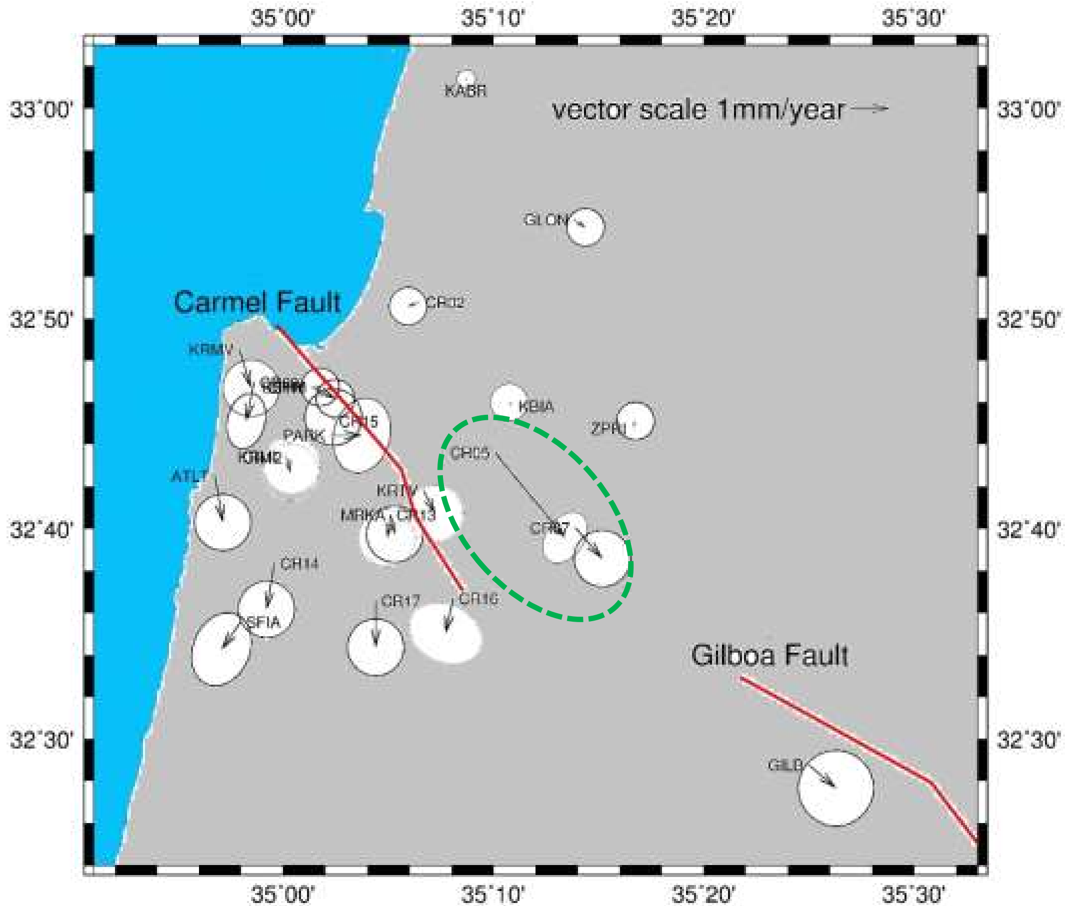
Discussion and Conclusions

- The velocity field clearly shows significant velocities in the region under investigation.
- In general, the horizontal velocity field shows deformations of about 1 mm/yr sinistral.



Discussion and Conclusions

- Points CR05 and CR07 show unexpected velocities – not compatible with the location of the faults.

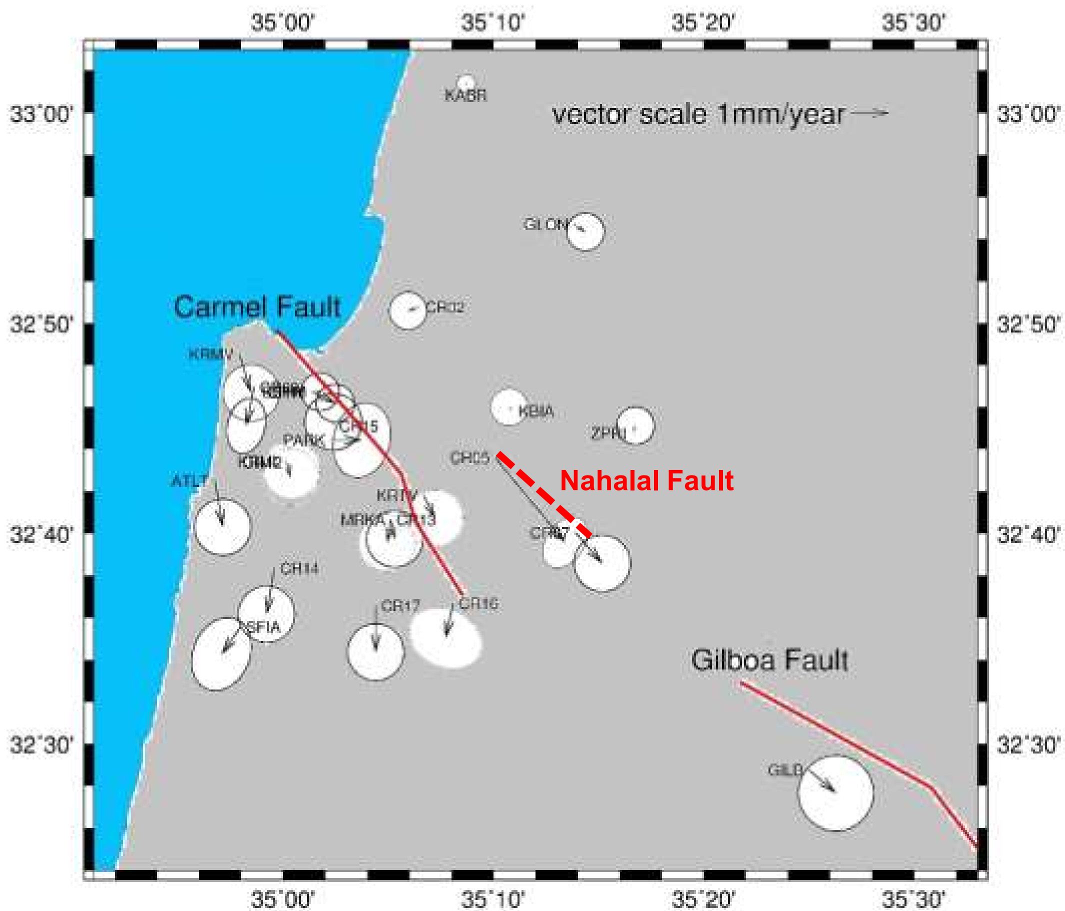


Discussion and Conclusions

- The velocity of point CR05 is anomalous but it has the same direction as CR07.
  - ✗ gross errors in the time series of the point location
  - ✗ slope failure or rockslide
  - ✓ local site effect and “real” deformation

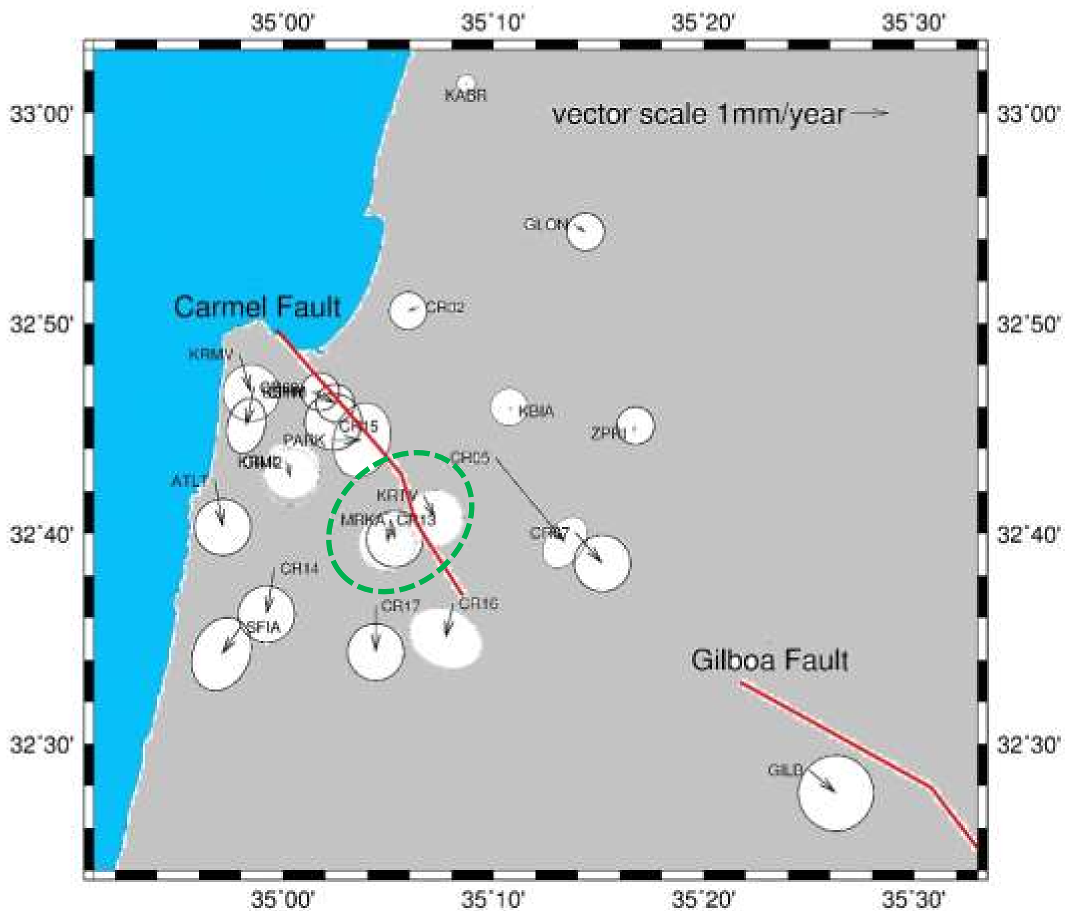
Discussion and Conclusions

- We would suggest that the significant velocity of CR07 and CR05 are the result of a deformation related to Nahalal fault.



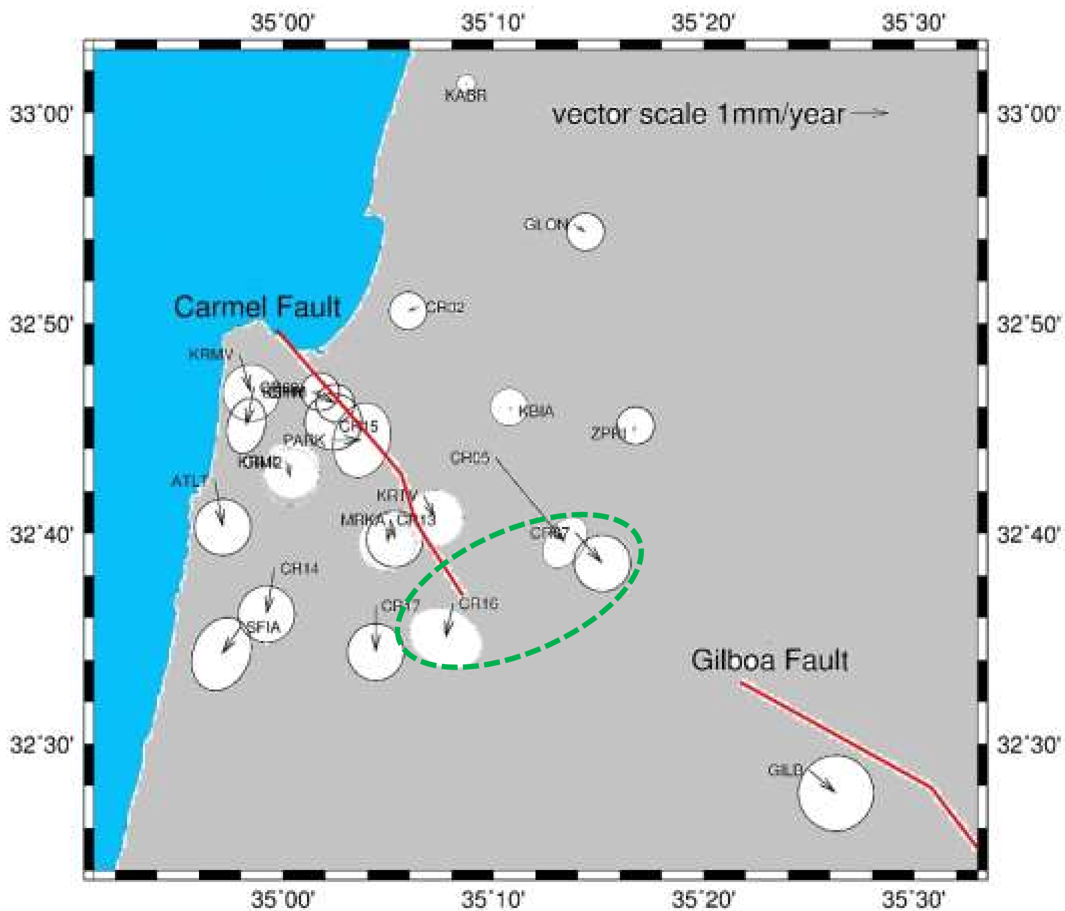
Discussion and Conclusions

- MRKA and CR13 on the south side of CF (Mount Carmel) and KRTV on the north side (Tivon Hills) show no significant velocities.



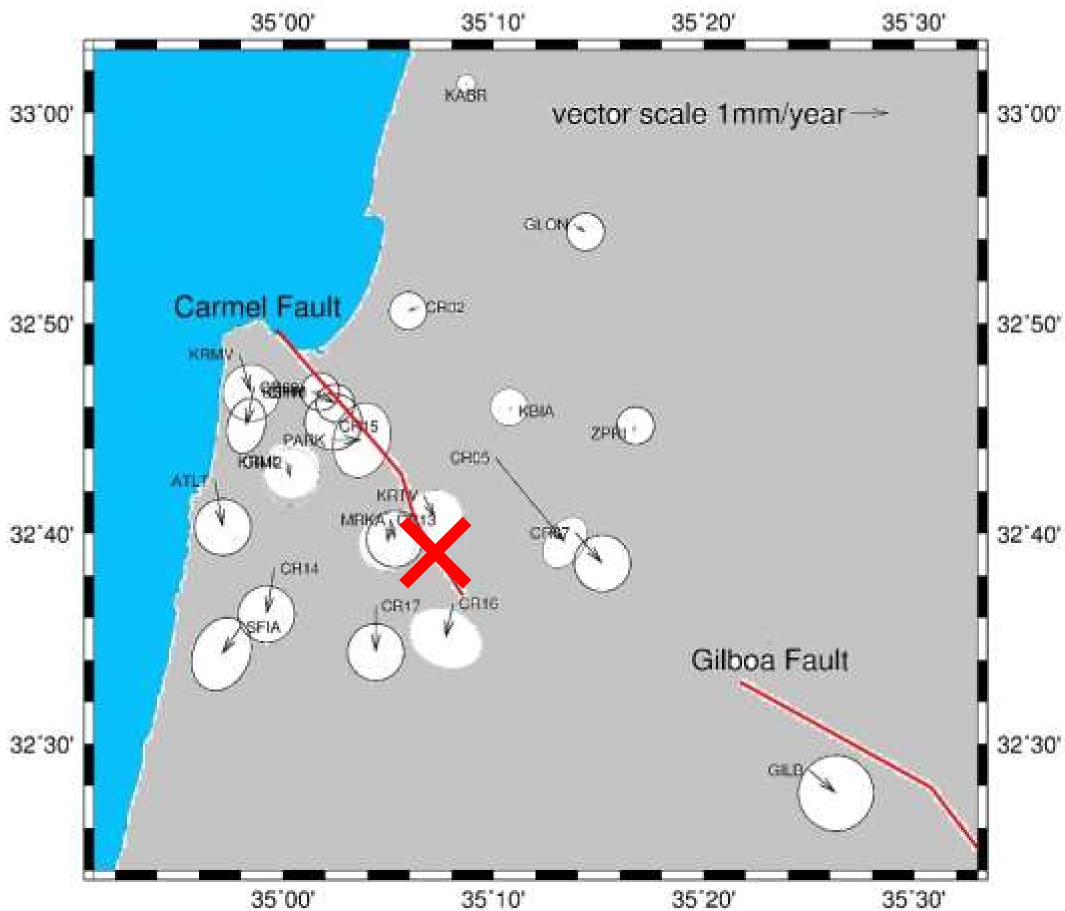
Discussion and Conclusions

- Points CR07 and CR16, which are located on both sides of the Yizre'el Valley as well as on both sides of the CF, show the same velocities in the same direction relative to the datum points.



Discussion and Conclusions

- This may indicate that the south segment of CF is not active and the velocities in the Yizre’el Valley region are due to activities along the GF or similar trending faults, which are halted by the Tivon Hills.



Summary

- Velocity field is estimated based on a time series of monitoring campaigns measured by means of GPS.
- The creation of an accurate and reliable velocity field with respect to a local datum is based on:
    - ► Eight monitoring campaigns that were measured between 1999 and 2016.
    - ► Eight-hour measurement sessions.
    - ► Measuring each network point at least twice in each campaign.
    - ► Using sophisticated mathematical tools.

The CG Fault System is a left-lateral slip with a velocity of about 1 mm/yr