Pre and co-eruptive deformation field at Merapi volcano from kinematic GPS surveys in the summit area

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Abstract

Merapi volcano (Java, Indonesia) is in almost continuous activity with growth of an andesitic lava dome inside a horse-shoe shape crater. To monitor the evolution of near field surface displacements and to model the associated magmatic sources parameters, we established starting 1999 a new strategy based on a dense network of about 50 benchmarks measured with a combination of static and kinematic GPS positioning. The measurement of this network takes only few hours (when summit access is possible), and brings a 1.5-cm error on the three-component displacement vectors. Data processing has been automated in order to be easily used as one of the monitoring techniques by the observatory.

We present the results of 16 surveys from 1999 to 2007, a period that includes two eruptive episodes in 2001 and 2006. Our results show large pre-eruptive and co-eruptive displacements associated to these eruptions, and evidence for deep fracturing in the vicinity of the main crater rim.

Methodology

Rock slopes monitoring need a **dense geodetic network** and **brief campaign** at summit. We developed a simple method using the following characteristics:

- GPS dual-frequency small receivers
- About 50 benchmarks and very short baselines (< 500 m)
- Kinematic trajectories and rapid-static baselines with common points
- Joint adjustment of the network positions
- Automatic processing routines for fast interpretation (*Matlab*)

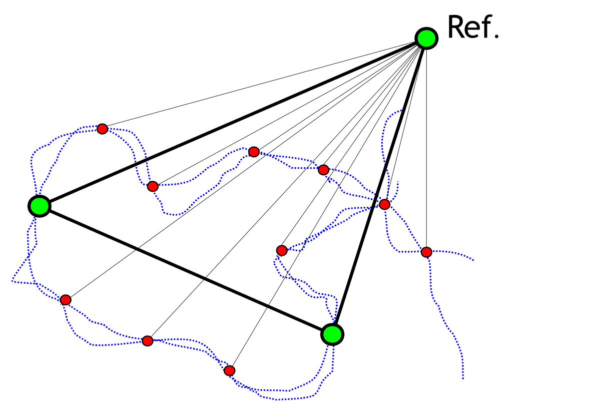

Figure 6. Principle of the measurement method (both 1-s sample rate): **(1)** Kinematic (red dots): ~50 points, 2-min measurements, < 5 cm precision. Points are all measured at least 2 times, along the trajectory which has to be closed (blue dashed line). **(2)** Rapid-static (green dots): at least 3 closed baselines between benchmarks common with kinematic, 15-min measurements, < 1 cm precision.

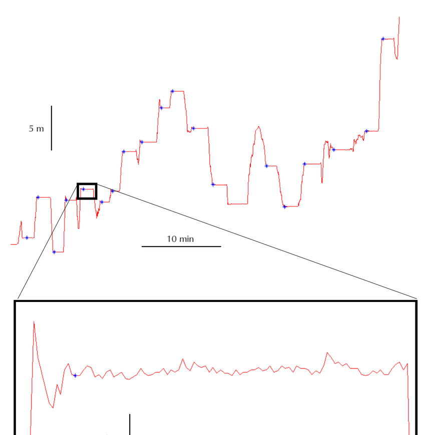

Figure 7. Example of trajectory measurement and processing: marks detection (blue stars), position extraction (3 component average and standard deviation), and automatic point recognition and naming.

$$\mathbf{AX} \approx \mathbf{B}$$
$$\mathbf{X} = (\mathbf{A}^T\mathbf{V}^{-1}\mathbf{A}^T)^{-1}\,\mathbf{A}^T\mathbf{V}^{-1}\mathbf{B}$$

$$A = \begin{pmatrix} 1 & 0 & 0 & -1 & \dots \\ 0 & 1 & 0 & 0 & -1 \\ 0 & 0 & 1 & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots \end{pmatrix} \qquad X = \begin{pmatrix} x_i \\ y_i \\ z_i \\ x_{i+1} \\ \dots \end{pmatrix}$$

$$V = \begin{pmatrix} \sigma_x^2 & \sigma_{xy} & \sigma_{xz} & \dots & \dots \\ \dots & \sigma_y^2 & \sigma_{yz} & \dots & \dots \\ \dots & \dots & \sigma_z^2 & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots \end{pmatrix} \qquad B = \begin{pmatrix} x_i - x_{i-1} \\ y_i - y_{i-1} \\ \dots \\ x_a - x_b \\ \dots \end{pmatrix}$$

Figure 8. Network adjustment is solved by simple least square linear system, where: **A** = partial derivatives, **B** = observations, **V** = covariance matrix, **X** = unknown (points coordinates *x*, *y*, *z*). Matrix **B** is constructed with differential baselines components (from point *i* to point *i*+1) for kinematic measurements, and baselines components (from point *a* to point *b*) for rapid-static measurements.

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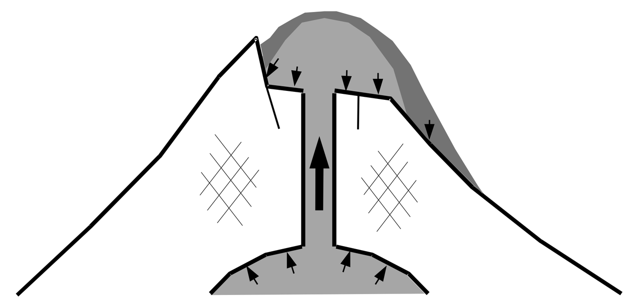
Introduction

Volcanic eruption and rock slope problems forecasting needs:

- Direction and magnitude
- Source type (magmatic / phreatic)
- Precise area localization (volume)



Answers come from monitoring observations combined with an interpretative model. But numerical models need **boundary conditions**, i.e., internal substructures geometry (magma chamber, duct and fractures) and source parameters (pressure and stress state). Because volcano edifices deform due to fluid transport (magma, gas, or water), these parameters can be partially retrieved from the deformation field analysis.

Merapi Volcano, Indonesia

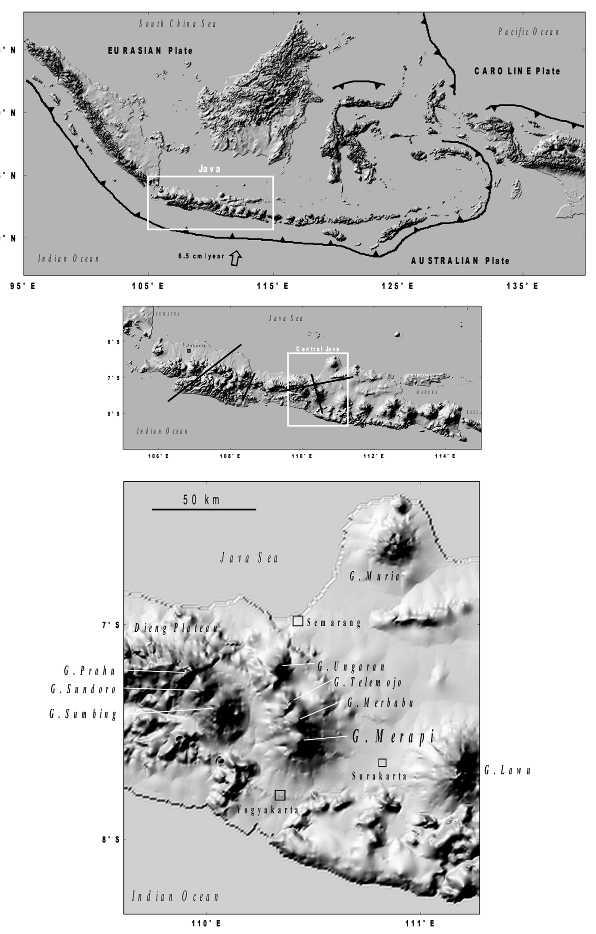


Figure 2. Merapi presents an activity of quasi continuous extrusion of lava which forms a dome in a horse-shoe shaped crater. The dome is continuously and partially destroyed by avalanches and pyroclastic flows. **(up)** View of Merapi from the South-East. **(bottom)** The January 30, 1992 lava dome: An almost perfect hemisphere of 140-m wide and 40-m high [photo *J. Tondeur*].

Figure 1. Location and geodynamical context of Mt. Merapi (2964 m). Merapi is a young strato-volcano located in Central Java, Indonesia, in a frontal subduction zone. Population of Yogyakarta (25 km from the summit) and around is about 3 millions people, up to 500,000 are living directly on the flank of the volcano, above 500 m of elevation.

Summit deformations 1988-1997

Merapi summit deformations have been observed by American, Indonesian and French teams using EDM since 1988 [*Young et al.*, 2000] and GPS measurements since 1993 [*Beauducel et al.*, 2000]. Before the 1992 dome growth episode, horizontal displacements reached 1.2 m/year, associated with strain rate of 11.10^{-6}/day. Main discontinuities have been roughly localized and modeled from 1993 to 1997 GPS observations, using 3-D boundary elements method [*Cayol and Cornet*, 1997].

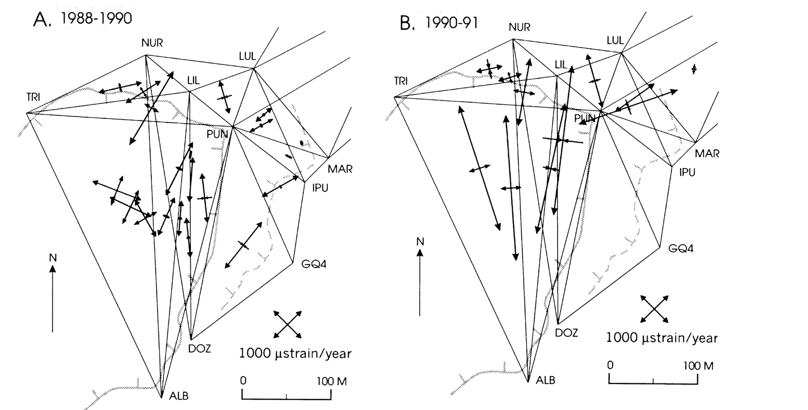


Figure 3. Principal directions and values of the strain tensors for selected triangles of the summit network, computed from EDM measurements: **(A)** June-July 1988 - September 1990 and **(B)** September 1990 - August 1991 [After *Young et al.*, 2000].

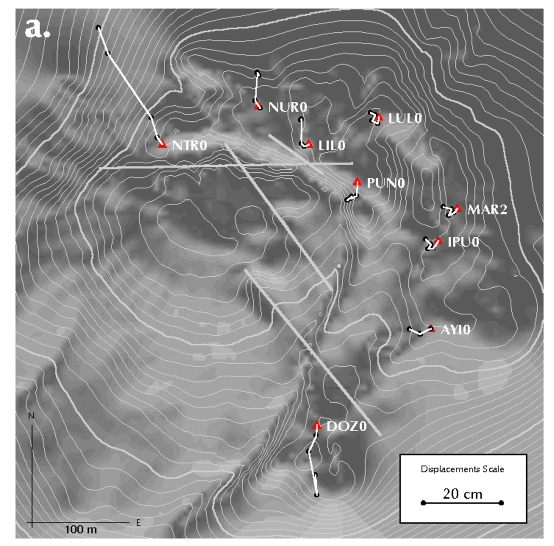
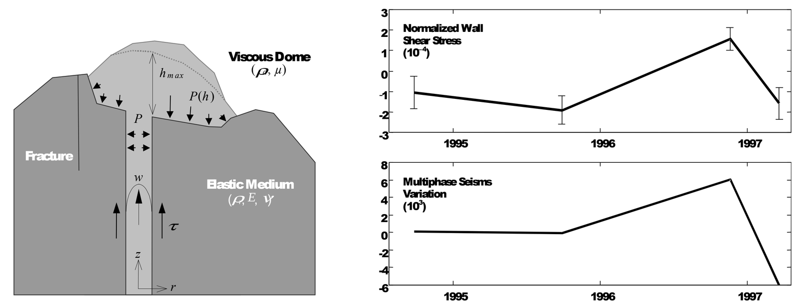


Figure 4. Cumulated horizontal GPS displacements at the summit from 1993 (red triangles) to 1997. An important movement occurred (about 40 cm) on the Northern part of the crater rim. Four “ independent ” zones separated by fractures (grey lines) with different behaviour are observed, presenting a deformation pattern similar to previous measurements (see Figure 3). These fractures have been observed and localized at surface, and introduced into 3-D numerical modelling The Northern zone did not exhibit an elastic behaviour; this was interpreted as a rock slope problem, just before this zone effectively collapsed in July 1998 [after *Beauducel et al.*, 2000].

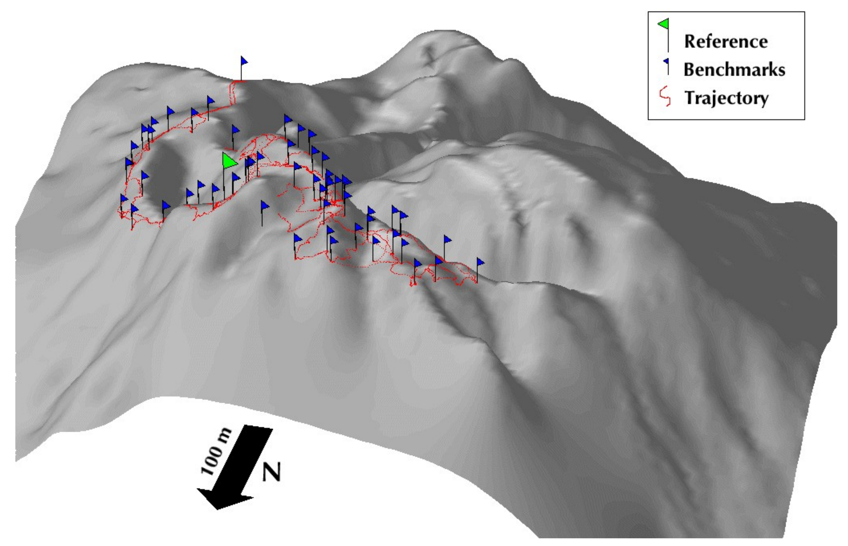
Figure 5. (left) Types of source considered for the summit modelling of displacement field: dome weight effect on the crater floor, magma pressure in the duct and wall shear stress due to flux variation of viscous fluid. Computation of the dome weight effect for 1993-1994 period showed that this effect is negligible on displacements. **(right)** We processed an inversion from the linear combination of the two forward problem solutions (pressure and wall shear stress in the duct) constrained by the 1993-1997 GPS 3-D displacements. The computed wall shear stress variations are compatible with recorded “multi-phase” seismic events variations. Because the two observations are independent, this gives further support that these seismic events are related with shear stress release at the duct wall [after *Beauducel et al.*, 2000].



New network and procedure

The new GPS network has been implanted in December 1999 with about 50 new benchmarks (geodetic 12-cm nails hammered in the lava blocs) around the main crater rim. It has been measured successively in 2000 (March, May, June, July, August and November), 2002 (October), 2003 (August), 2004 (August and December), 2005 (June, July and September), 2006 (March), and 2007 (January). During January 2001 and April 2006 eruptions, access to summit was prohibited for security reasons. Rapid-static baselines and kinematic trajectories are first processed using commercial GPS software (coming with *Sercel* receivers), to output simple coordinates files. Then automatic *Matlab* routines have been developed to extract kinematic positioning data and make the join inversion. This allows producing numerical results and graphics within few hours just after each field campaign, making this procedure usable for monitoring purposes.

Figure 9. The new GPS network at Merapi summit: reference LUL (green flag, is one of the 1988 EDM-network point), benchmarks (blue flags) and example of trajectory for one campaign (red line). Only Northern and Eastern zones of the crater rim can be monitored, due to strong topography, gas emissions and dome activity. The Southern zone is too dangerous to access due to rock avalanches since 1997.



Conclusions & Perspectives

- Uncertainties after joint adjustment (kinematic + static) < 1.5 cm for the entire network and 3 components East, North, Up. The method needs at least 2 trajectories and 3 rapid static baselines (1-day campaign).
- Significant displacements (maximum 1.75 m) are detected and associated with magma production. Displacement field is sufficiently dense to reveal major discontinuities into the edifice and identify stable zones.
- Almost all the benchmarks have disappeared during centennial eruption in 2010, that deeply modified the summit morphology.

Results : Displacements field from Dec. 1999 to Jan. 2007

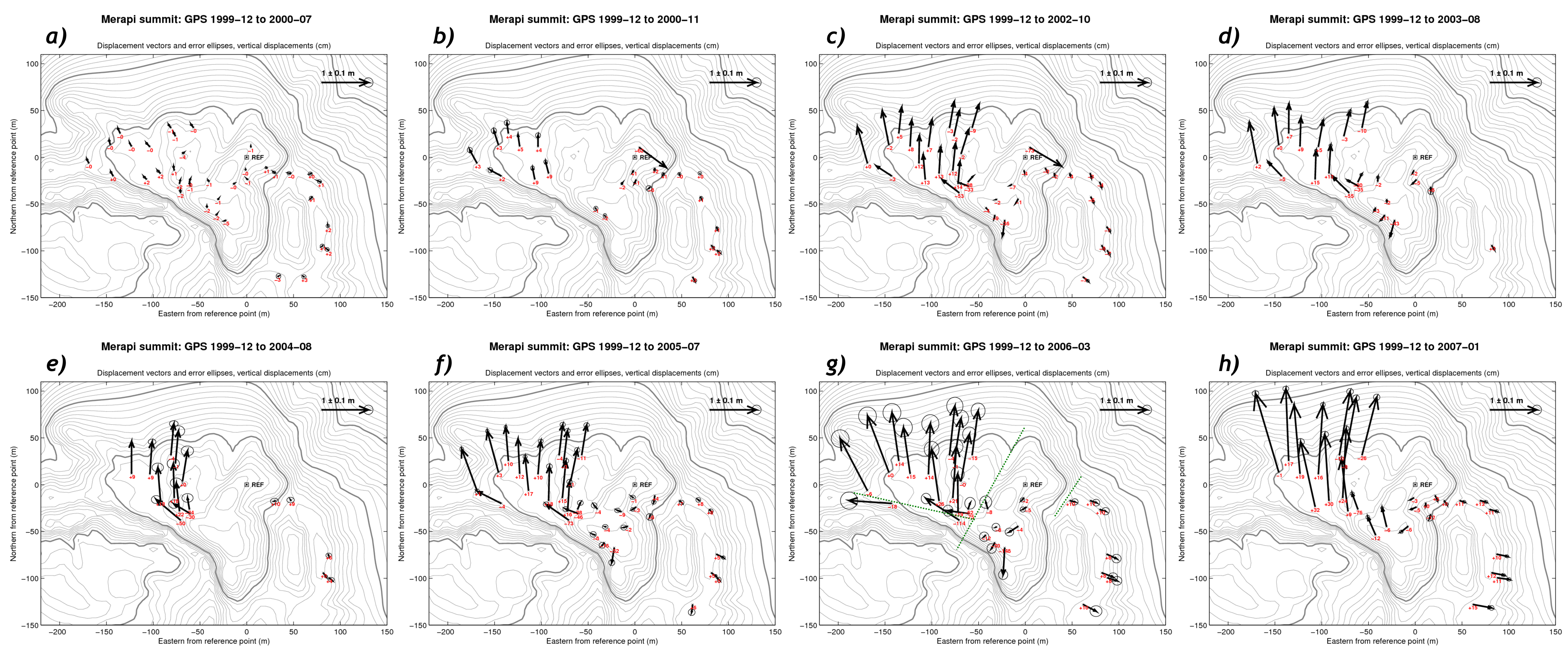


Figure 10. Relative horizontal displacements and uncertainties (95% error ellipses), and vertical displacements in cm (numerical values in red, positive for up). ***a)*** to ***h)*** are displacements from 8 campaigns carried on between March 2000 and January 2007 (see dates in each figure title), relative to the first campaign operated in December 1999. Maximum vectors reach 1.75 m in amplitude, mostly horizontal. ***i)*** and ***k)*** presents co-eruptive signals of the January 2001 and April 2006 eruptions, respectively. ***j)*** is the inter-eruptive signal. Some fractures are indicated in dashed green. Note about ***g) j) k)*** error ellipses: due to field problems during March 2006 session, the rapid-static measurements were not usable; large uncertainties correspond then to kinematic baselines only, but signal/noise ratio is still acceptable.