TERRAFIRMA
6th USER WORKSHOP

Greek group:
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Use of displacement space measurements in geotechnical engineering: Application at Thessaly plain

Geotechnical engineering problems often concern ground displacements. The methodology used to predict future displacements includes the following steps:

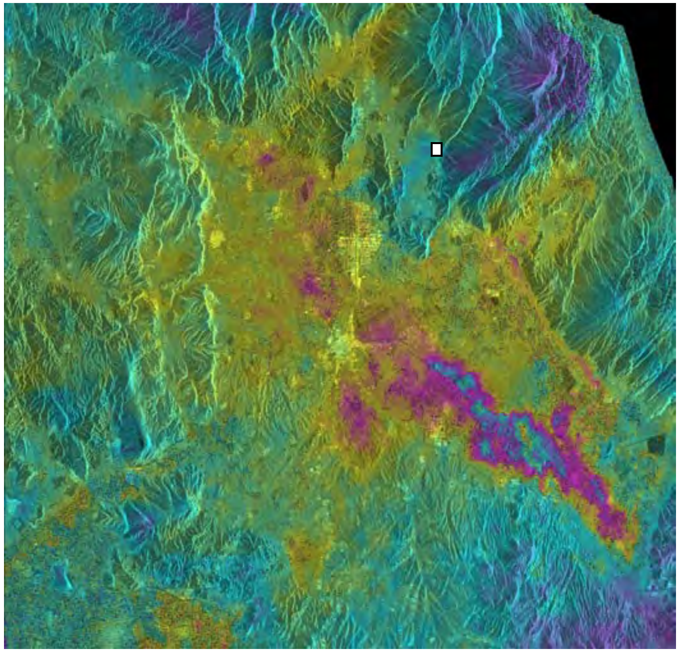
a. Propose a geotechnical model that predicts the mechanism that causes ground displacement at the problem under consideration. Estimate the parameters of the model based on available geotechnical data.

b. Use the model and parameters to predict ground displacement.

Ground displacement past data is not usually used in geotechnical design, as it is usually not available. Satellite technology provides past ground displacement data in a cost-effective manner. Based on these displacement measurements an improved geotechnical design approach can be proposed. It includes the following steps:

- 1.Propose a geotechnical model that simulates the mechanism that causes ground displacement. Estimate the parameters of the model based on available geotechnical data.
- 2.Validate the proposed model and its parameters by the prediction of the past ground displacement data. Make adjustment of model or parameters where necessary.
- 3. Use the validated model and parameters to predict future ground displacements.

Alternatively, satellite measured displacements alone cannot predict with confidence future displacements. Only thru proper modelling of the mechanism of generation of ground displacement, past displacement data can be used to predict future displacement in a reliable manner: Past displacement data can determine soil parameters and/or verify the geotechnical model assumed and this model with these parameters can be used to predict future displacement under different loading scenarios.



- To illustrate the manner that this improved design approach above can be applied, the case of the settlement of the Thessaly plain – Carla region - due to excessive pumping is examined.

The Problem appears in form of lengthy cracks or settlements at a number of villages

Platikampos

Chalki

Melia

Niki

Stefanovikio

Stavros

In the sites shown in the photos and other sites some approximate measurements of vertical displacements, width and depth of cracks were taken. Their range is given in the table below.

Site (village-town)	Vertical displacement (cm)		Width of crack (cm)	Depth of crack (cm)
	min	max		
Kalamaki			100	50-80
Platikampos	8	10		
Halki	10	80		
Melia	10	40		
Achilion	5	15		
Niki	10	40		
Stefanovikio			5-200	150
Rizomilos	2	50		
Farsala	2	15		
Stavros	4	150		

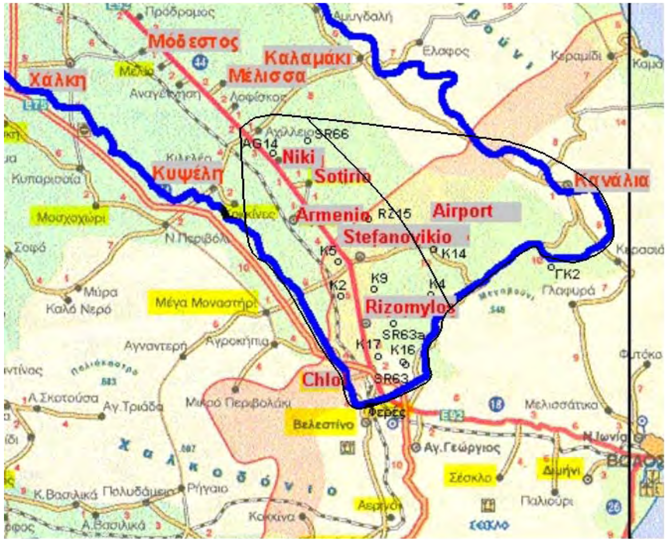
-Studies of IGME and observations strongly correlate soil settlements to systematic lowering of the water table due to water overpumping.

- No systematic correlation to tectonic causes has been recognized.

- The phenomenon is more pronounced in the Karla region.

Map of greater area of Thessaly

Map of Karla region



GEOTECHNICAL MODEL

The following assumptions were taken:

(a) Settlements are due to one-dimensional consolidation as a result of the increase of effective stresses due to the lowering of the water table line

(b) settlement is due to primary consolidation of clayey material only.

(c) Soil is normally consolidated.

(d) An average with depth degree of consolidation is assumed.

Basic equation predicting settlement is given below

The expression for the settlement is:

$$s = \sum_{i=1}^{n} \left[\frac{C_{ci}}{1+e_{oi}} \log \frac{\sigma'_{voi}+\Delta\sigma'_{vi}}{\sigma'_{voi}} \right] \cdot \Delta z_i$$

where:

σ'_{voi}	initial vertical stress at layer i
$\Delta\sigma'_{vi}$	additional vertical stress at layer i
C_{Ci}	coefficient of compressibility at layer i
e_{oi}	void ratio of soil of layer i
Δz_i	thickness of layer i

Here the change in vertical stress that causes consolidation is due to water level lowering therefore it is given as:

$$\Delta\sigma'_v = (\gamma_u - \gamma_w)\, \Delta H$$

where γ_u, γ_w the average bulk unit weight of soil and specific weight of water respectively, and ΔH the water level fall.

In addition the rate of settlement is determined as given below

Consolidation equations:

$$T_U = \frac{\bar{c}_v t}{H^2}$$

$$\bar{U} = 1 - \sum_{\mu=0}^{\infty} \frac{2}{M^2} e^{-M^2 T_U(t)}$$

$$M = \frac{\pi}{2} (2\mu+1), \quad \mu = 0, 1, 2, ...$$

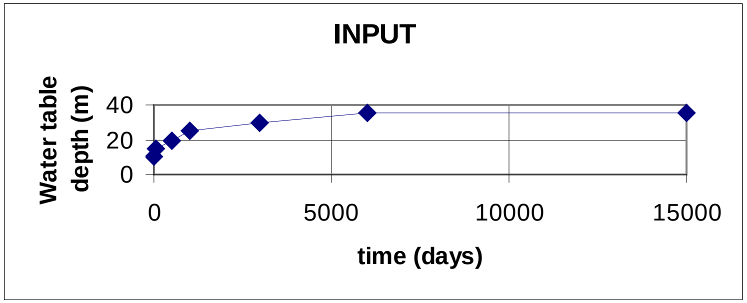
Two types of boundary conditions:
surface drainage
surface – bottom drainage.

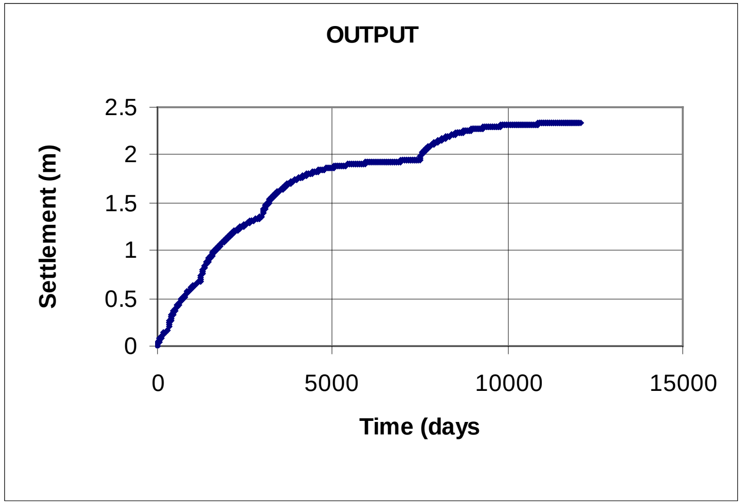
where:

$\bar{c}_v$ is the average with depth consolidation coefficient
$\bar{U}$ is the average with depth degree of consolidation
H is the drainage path

A FORTRAN computer program was written to calculate settlements in terms of time for given water table variation.

The water table is taken to vary with time and the equations are solved for each such variation. Superposition is used adding all solutions





Expressions relating measured values of physical properties of soil to geotechnical parameters used in the model are given below

$$C_C = 0{,}009\,(W_L - 10)$$

$$e = 2{,}7\,(W_L / 100) - C_C \log (\sigma'_{oct} / 7)$$

where:

$$\sigma'_{oct} = \sigma_v \frac{(1+2k)}{3}$$

$$k = k_o = (1-\sin\varphi')\,OCR^{\sin\varphi'}$$

$$\varphi' = 44{,}5\,\frac{1}{I_p} \quad (\text{in }^{o})$$

$$\tan\varphi' = 0{,}58 - 0{,}0045\,I_p$$

Analyses were performed for 3 cases

(1) Western Karla region

(2) Stefanovikio

(3) Chloi

For case (1) geotechnical date available from sites within the region were averaged.

Values of basic parameters for 3 cases runs were obtained by averaging available data

Area-site	Total thickness of clay layer	W_L	PI	C_C	c_v ($x10^{-7} m^2/sec$)			
W.Karla region	130	56.5	35.8	0.400	7.4			
Stefanovikio	120	56.5	35.8	0.400	7.4			
Chloi	130	51.9	33.8	0.350	7.4			

GEOLOGICAL AND GEOTECHNICAL DATA USED IS GIVEN IN BELOW

Sources of data:	Provided by
water drilling borings	Water Resources Dept. of Thessaly
sample drilling borings	KEDE, IGME
laboratory tests	KEDE, IGME

Geographical positions of data:

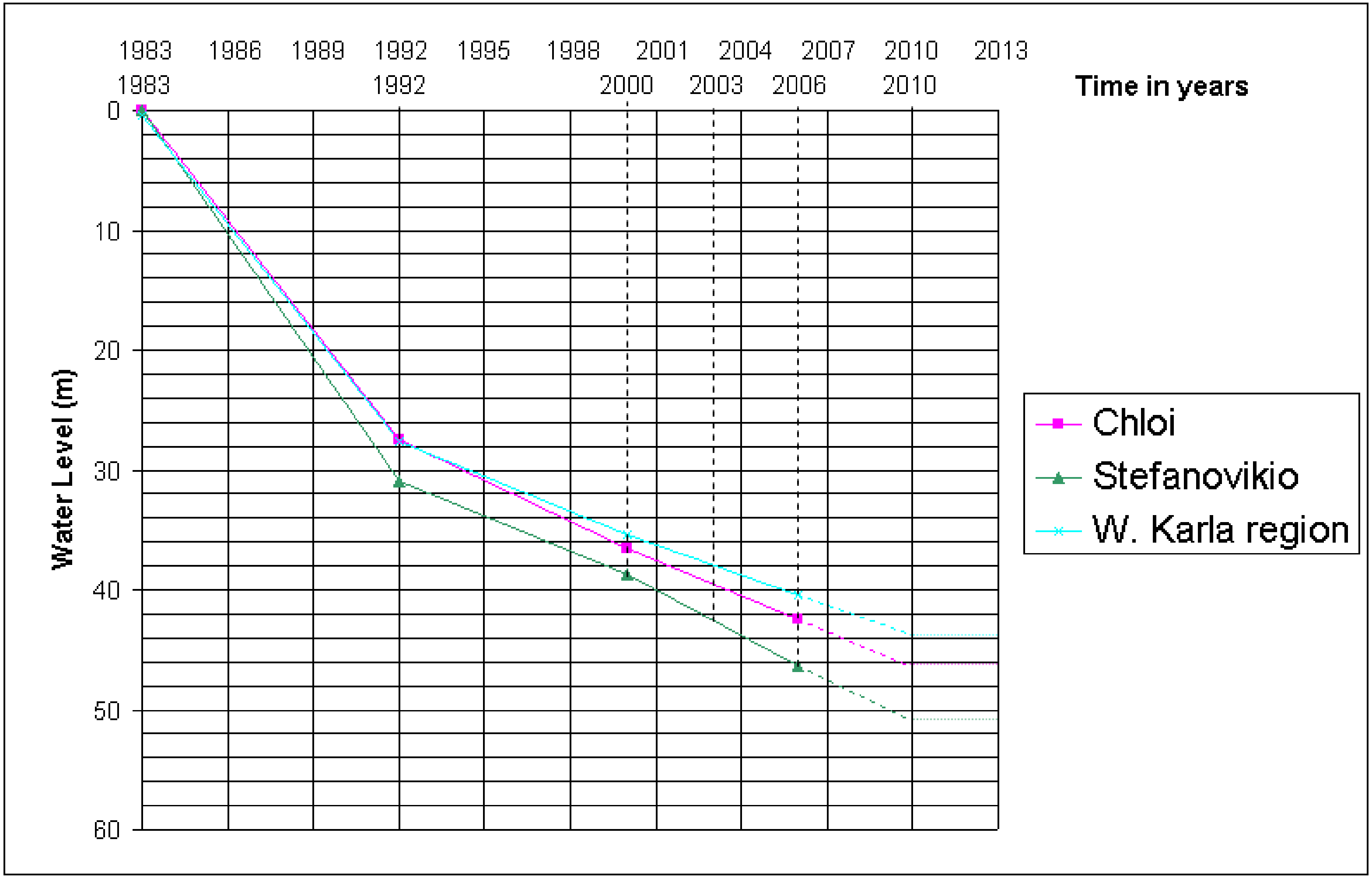
Water drilling borings (12)

Rizomylos	1	Panagia	1
Stefanovikio	3	Karagianeika	1
Sotirio(Nees)	2	Karasouloukia	1
Chloi	1	Retzikia	1
Niki(Akumia)	1		

Sample drilling borings and lab. tests (18)

Chloi overpass K.P. 5+923, Velestino Section, National Highway Lamia-Larisa	1
Karla ditch	6
Petra, Karla lake	1
Karla bridge	2
Platikampos dam	7
Kastri	2

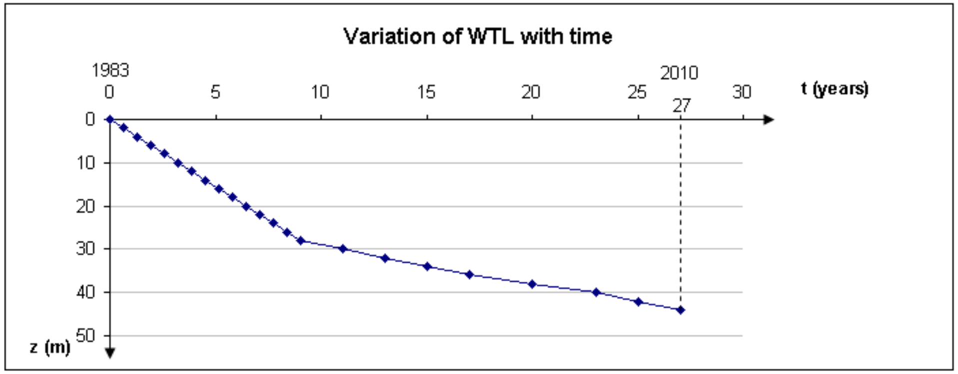
Ground water table level fall from 1983 to 2010 are given below. Seasonal fluctuations have been removed. Fall begins in 1983

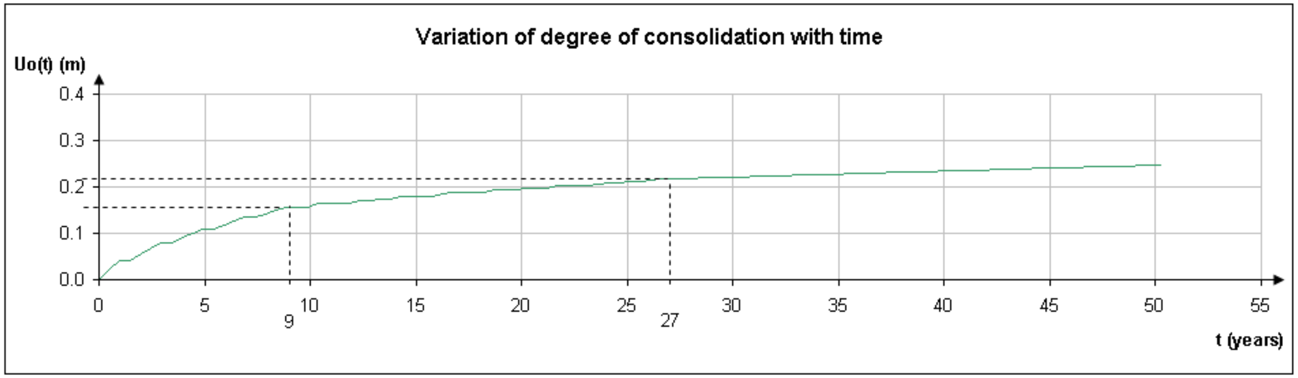


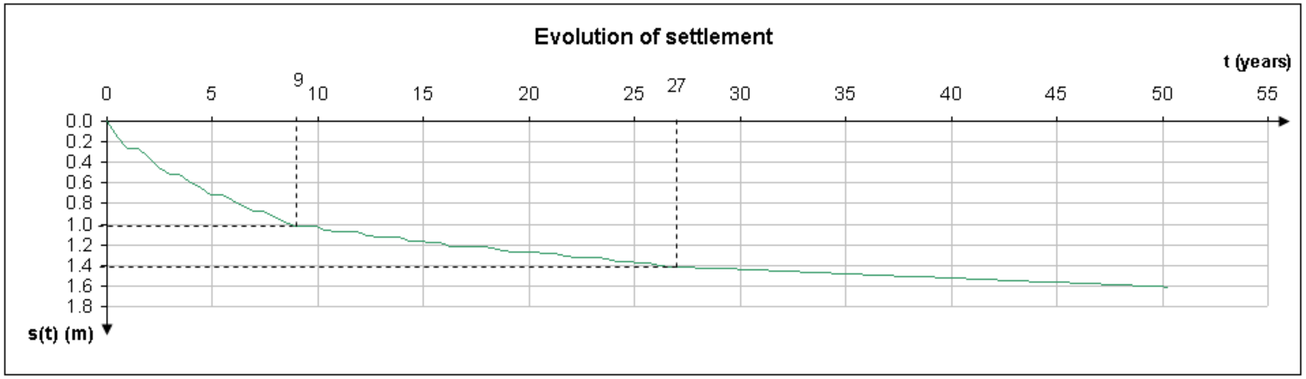
Settlements for the 3 cases, where t=0 is 1983 are given in the table below. The results are consistent with observed settlement described above

Area-site	s (t=9years) (m)	s (t=27years) (m)	s (t=50years) (m)
W.Karla region	1.0	1.4	1.6
Stefanovikio	1.0	1.4	1.7
Chloi	0.9	1.3	1.5

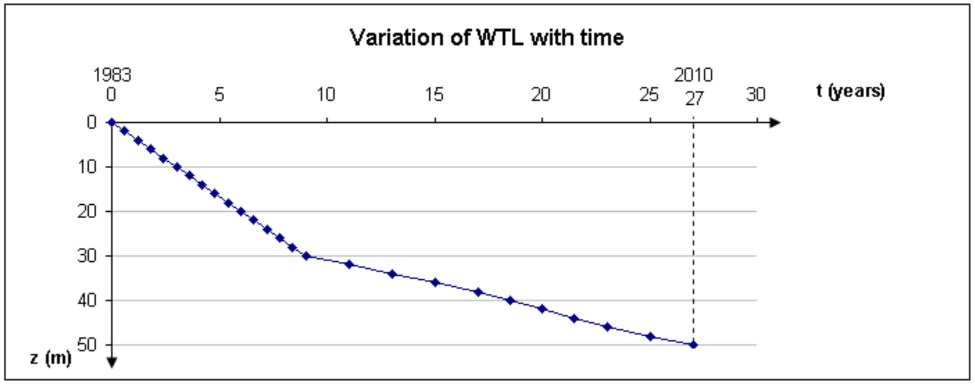
Water level, degree of consolidation and settlement variation with time for Western Karla region


Variation of WTL with time

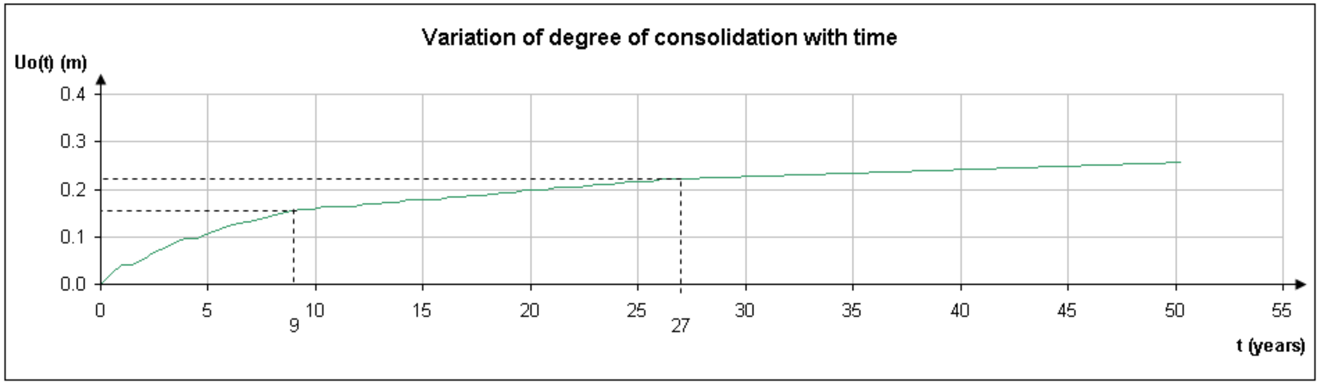

Variation of degree of consolidation with time


Evolution of settlement

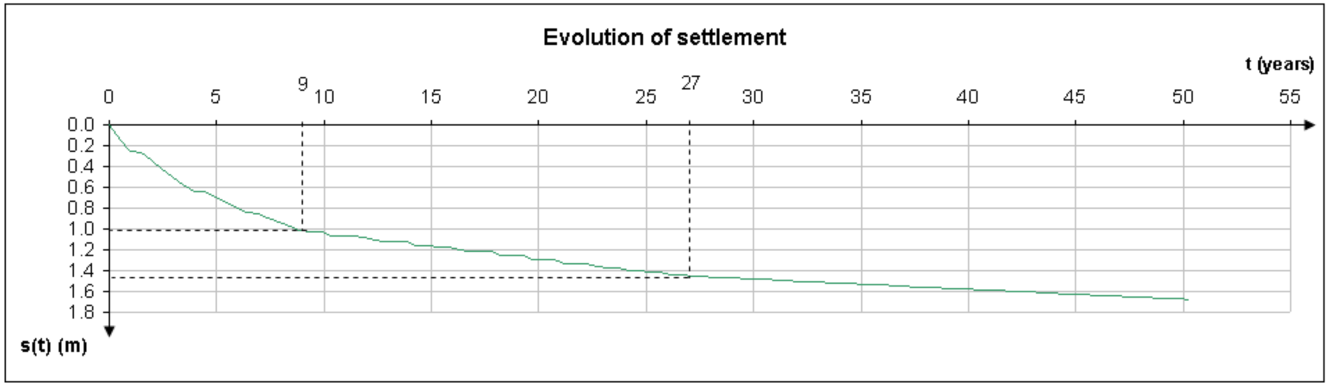
for Stefanovikio



Variation of WTL with time

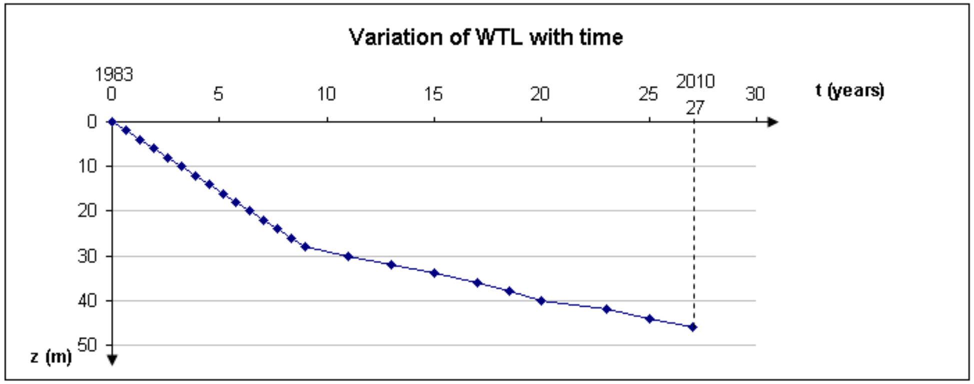


Variation of degree of consolidation with time

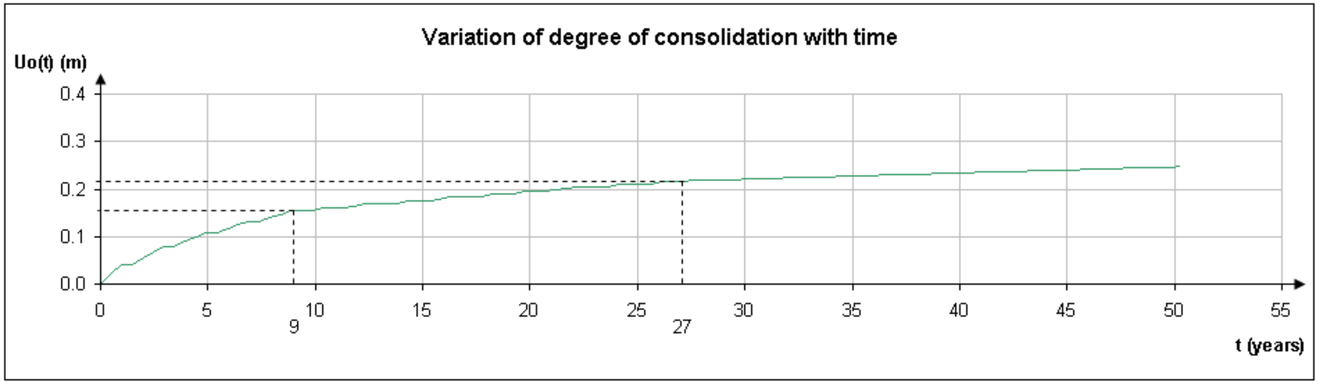


Evolution of settlement

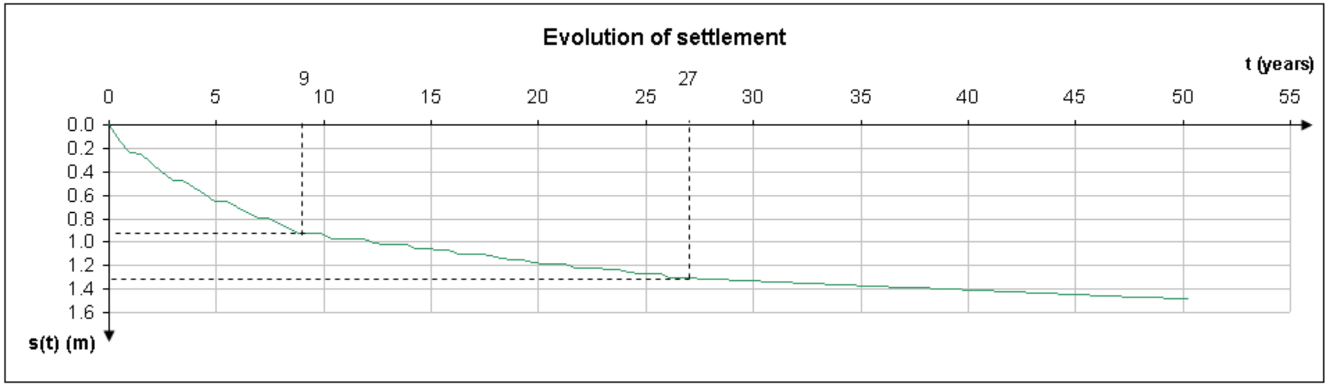
for Chloi



Variation of WTL with time



Variation of degree of consolidation with time



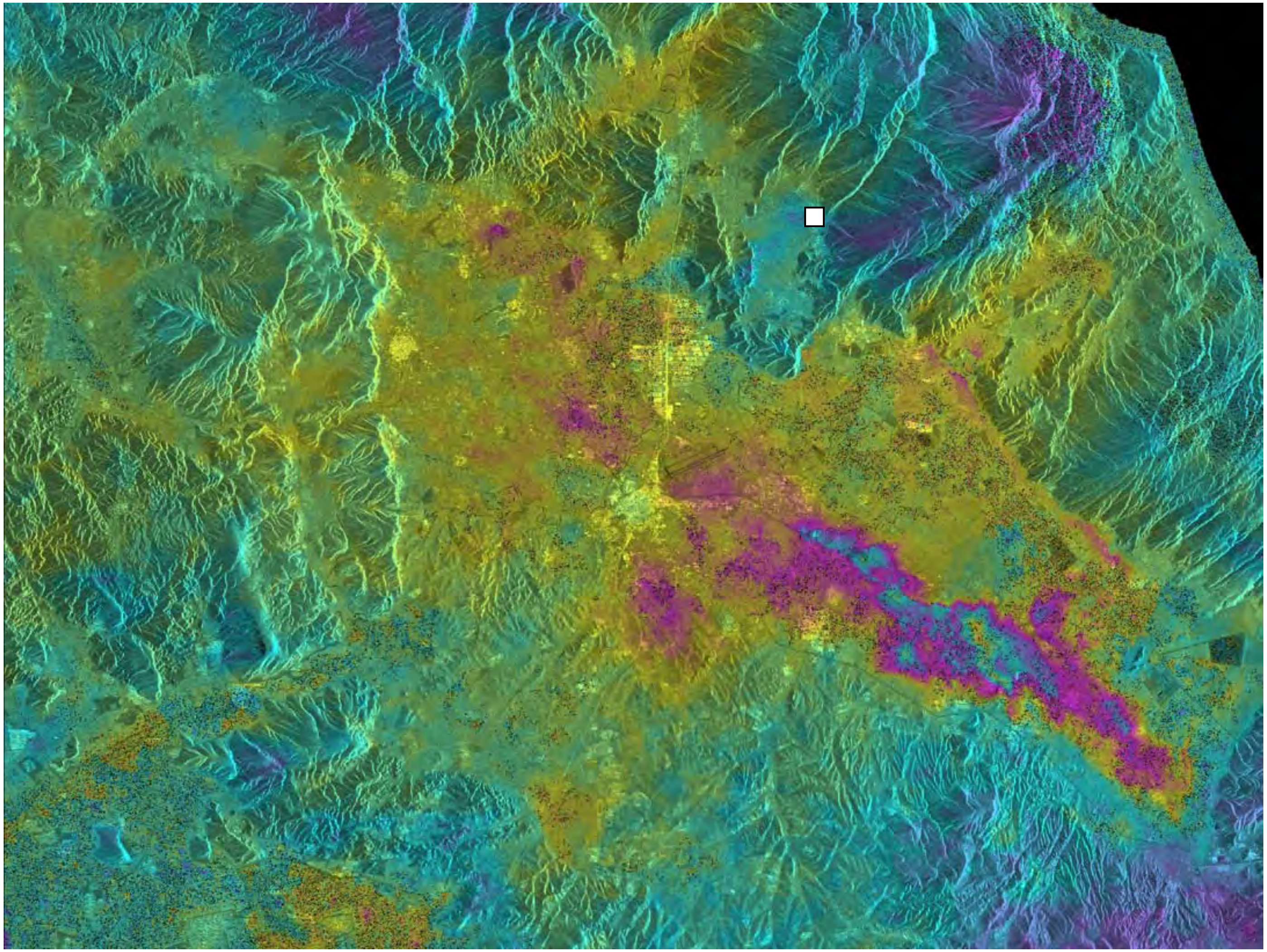
Evolution of settlement

Differential Interferograms

Displacements measurable using conventional differential interferograms

Significant displacements even within 35 days

Higher displacements during summer and fall seasons



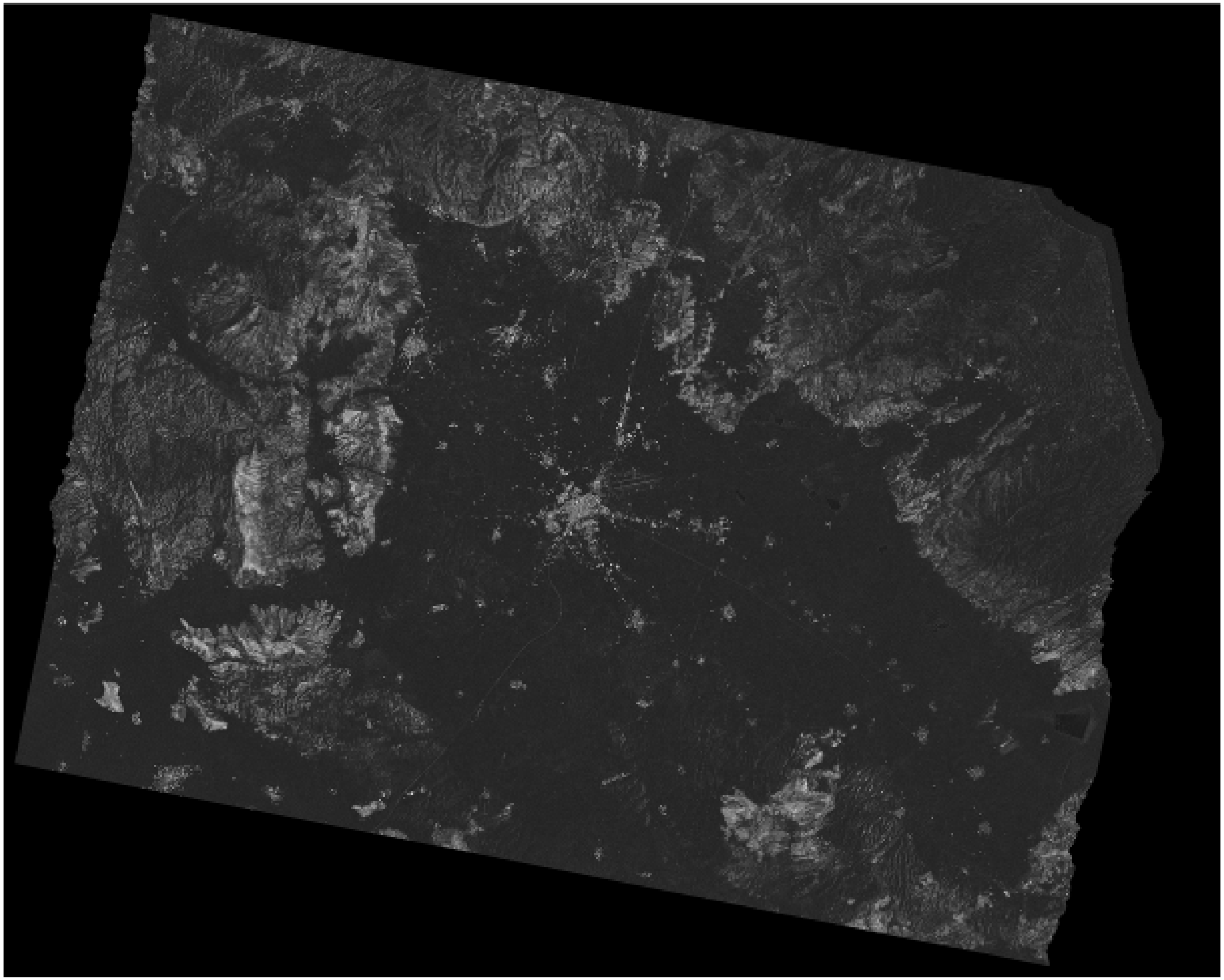
unwrapped
diff. interferogram
19980802-19980906
dt=35days
Bp~10m

maximum surface
displacement
-17,4 cm

Temporal Coherence Levels

Extended temporal decorrelation due to land cover characteristics

period 1992-2000



Data Used

48 ERS-1 & -2 SAR scenes and 24 ENVISAT ASAR scenes in descending mode covering the periods 1992-2000 and 2002-2010 respectively

Average multi-look (1x5) image of the region of interest in range-Doppler coordinates

Stacking procedure

Difficulties propagating PSI solution to the region of interest, due to temporal decorrelation and high deformation gradients

Seasonal variability of the displacement (magnitude and sing)

Stacking procedure applied as an alternative approach for estimation of linear deformation rates

Selection of interferometric pairs with small temporal separation (dt<=2yr) to reduce the amount of displacement within each pair as well as with perpendicular baselines <=50m to minimize topographic effects

Totally, 33 ERS-1 & -2 and 32 ENVISAT unwrapped differential interferograms were analyzed for the periods 1992-2000 and 2002-2010 respectively

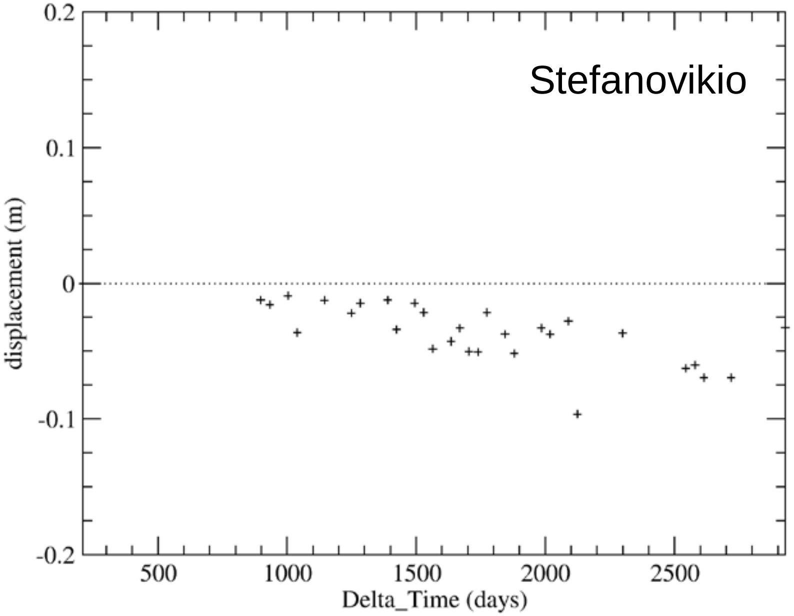
Alternative processing approach

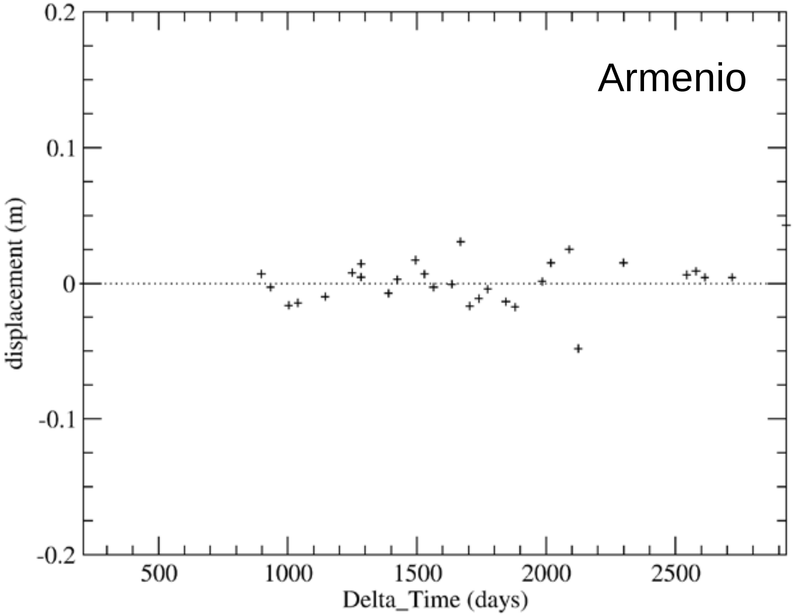
Calculation of least-squares solution by Singular Value Decomposition (SVG) for the phase time series, on a pixel basis, using spatially unwrapped multi-reference continuous differential interferograms.

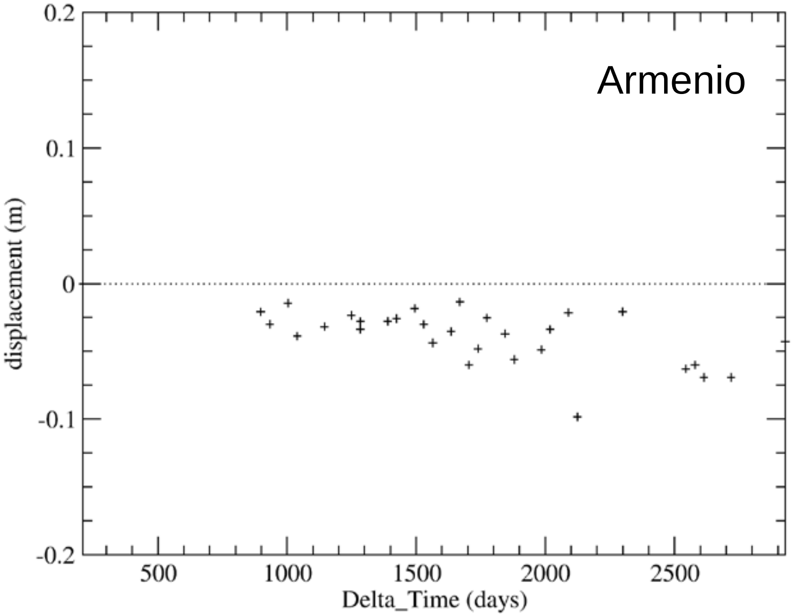
Displacement Time-series

Non-linear component of motion observed in the majority of the cases

Significant seasonal oscillations even for points with low linear deformation rates (shown relatively stable)





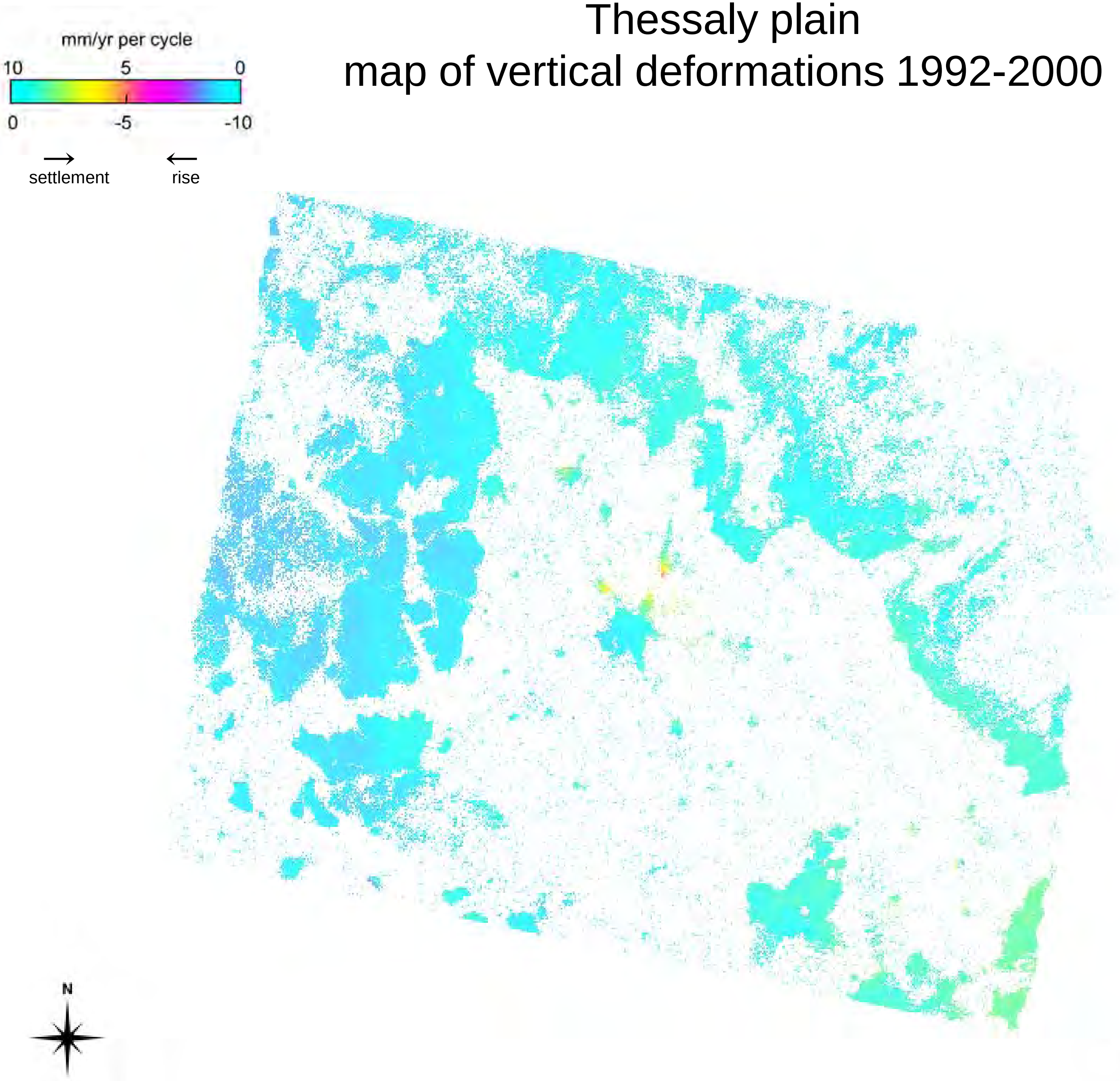


Measurements from satellite image recordings according to method of stacking of differential interferograms.

Period over which data are available: 1992-2010
divided to two sub periods:
subperiod: 1992-2000
subperiod: 2002-2010

Satellite images presented:
Thessaly plain
Karla region
Subregions-sites in Karla region

Thessaly plain
map of vertical deformations 1992-2000



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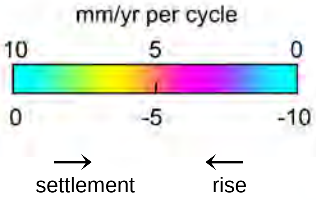
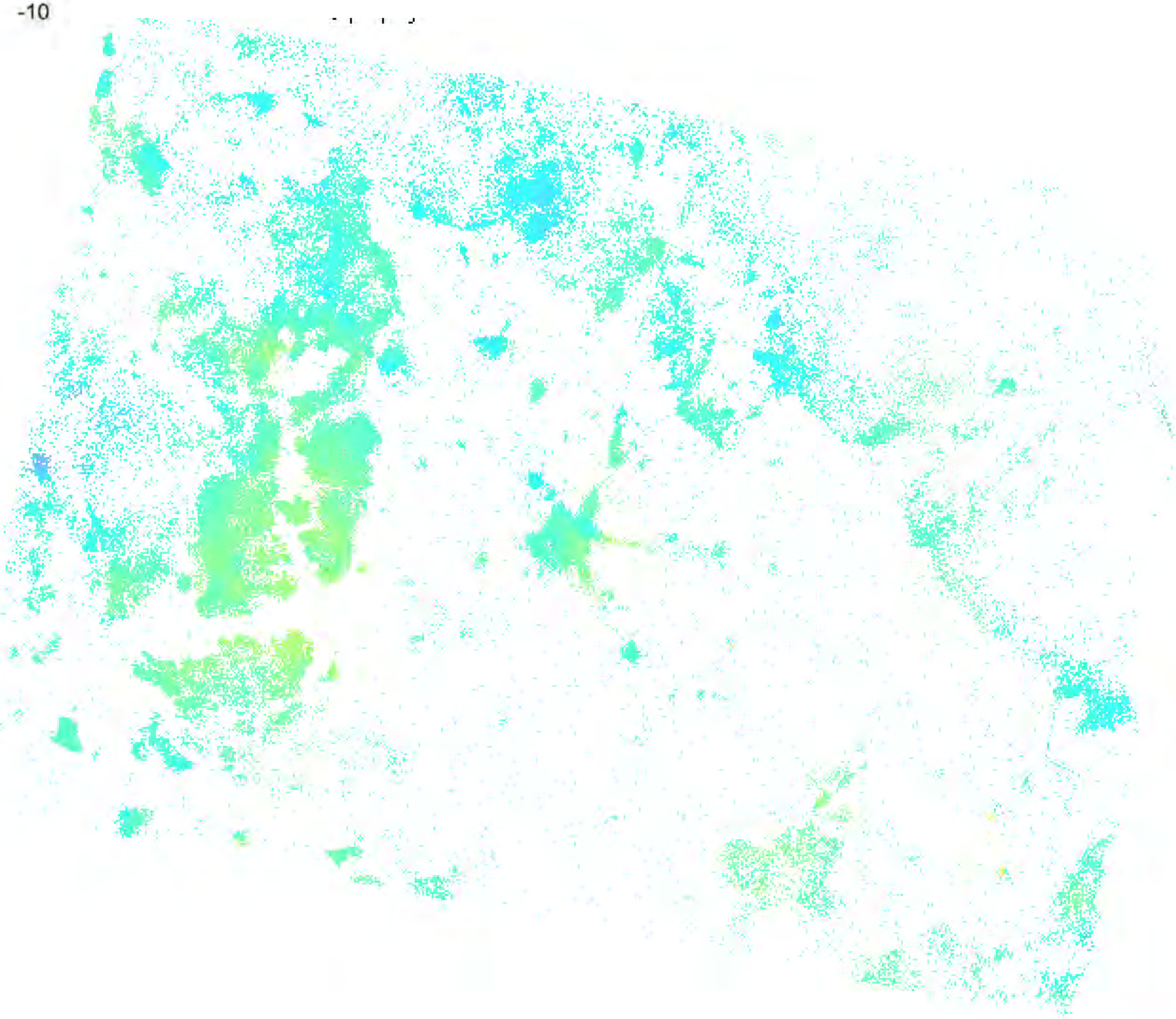
Thessaly plain
map of vertical deformations 2002-2010





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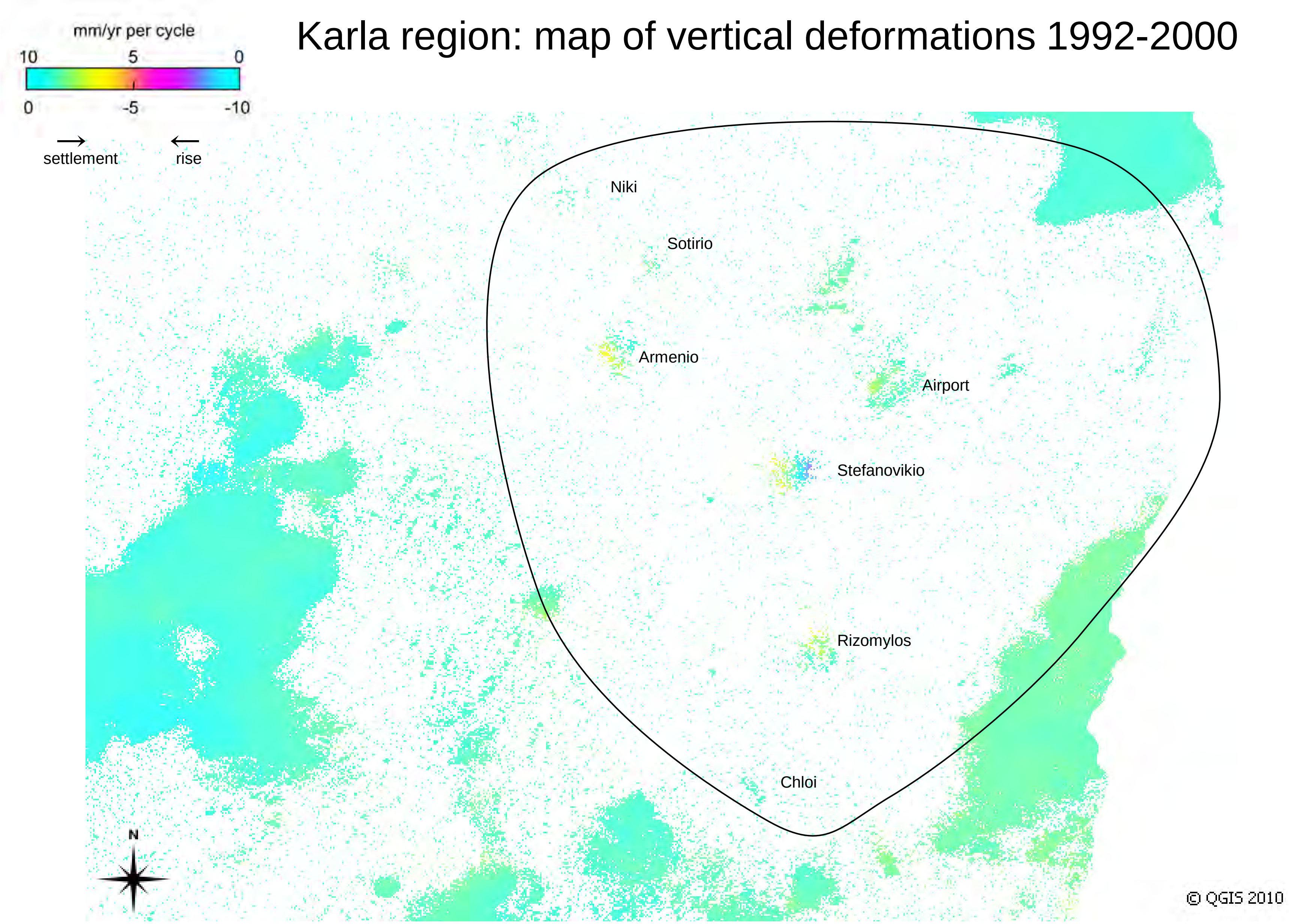
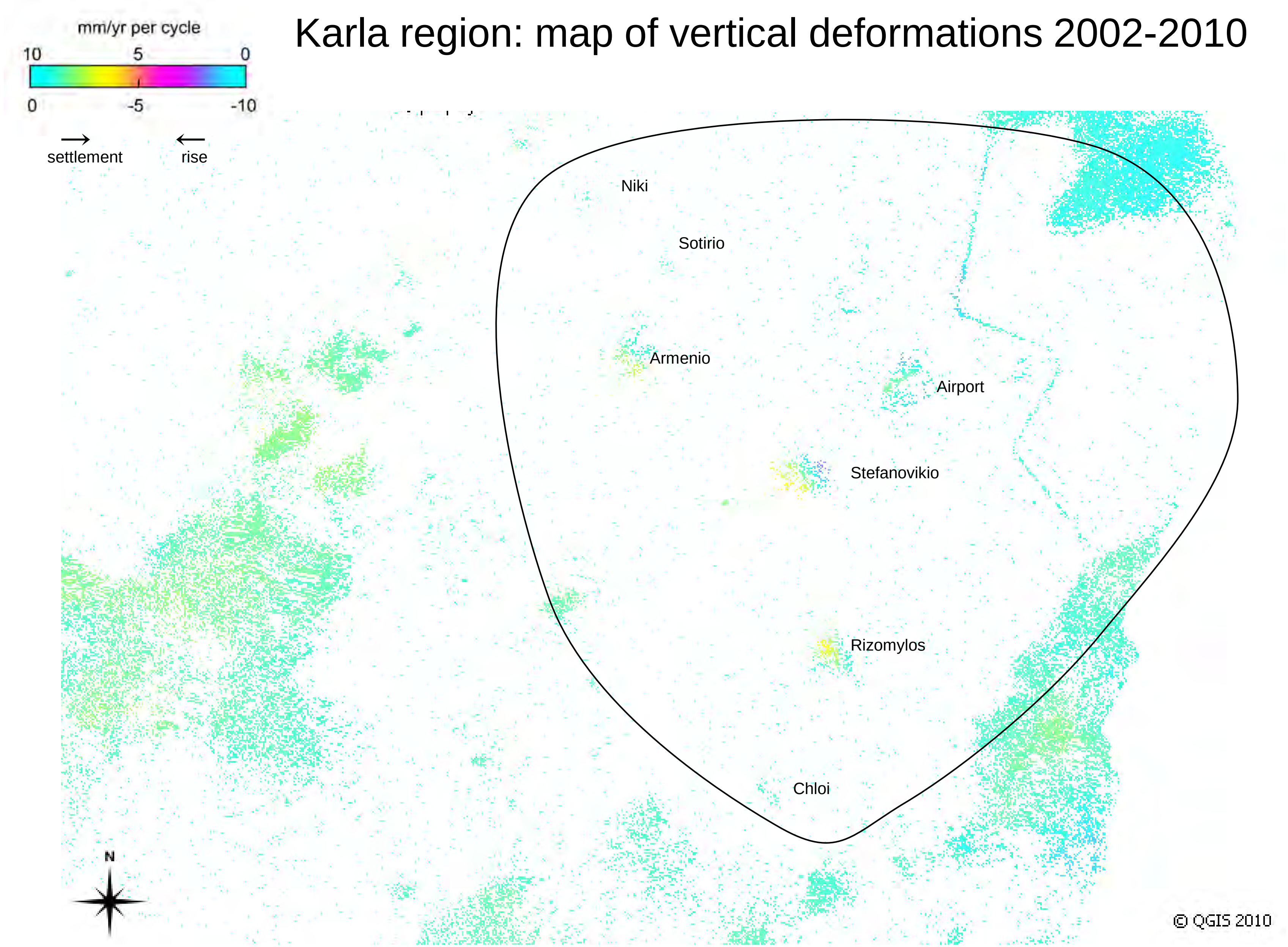
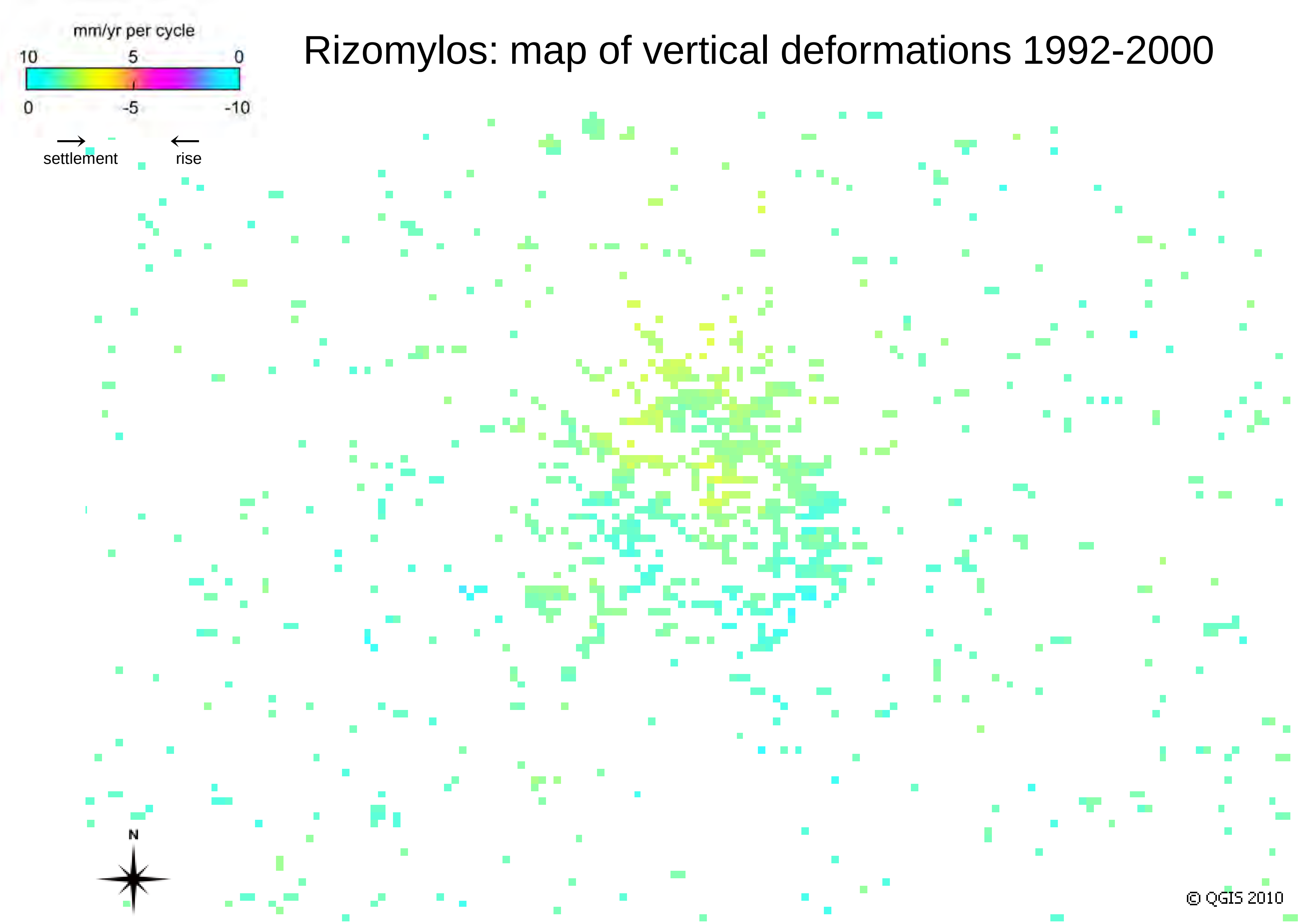
Karla region: map of vertical deformations 1992-2000



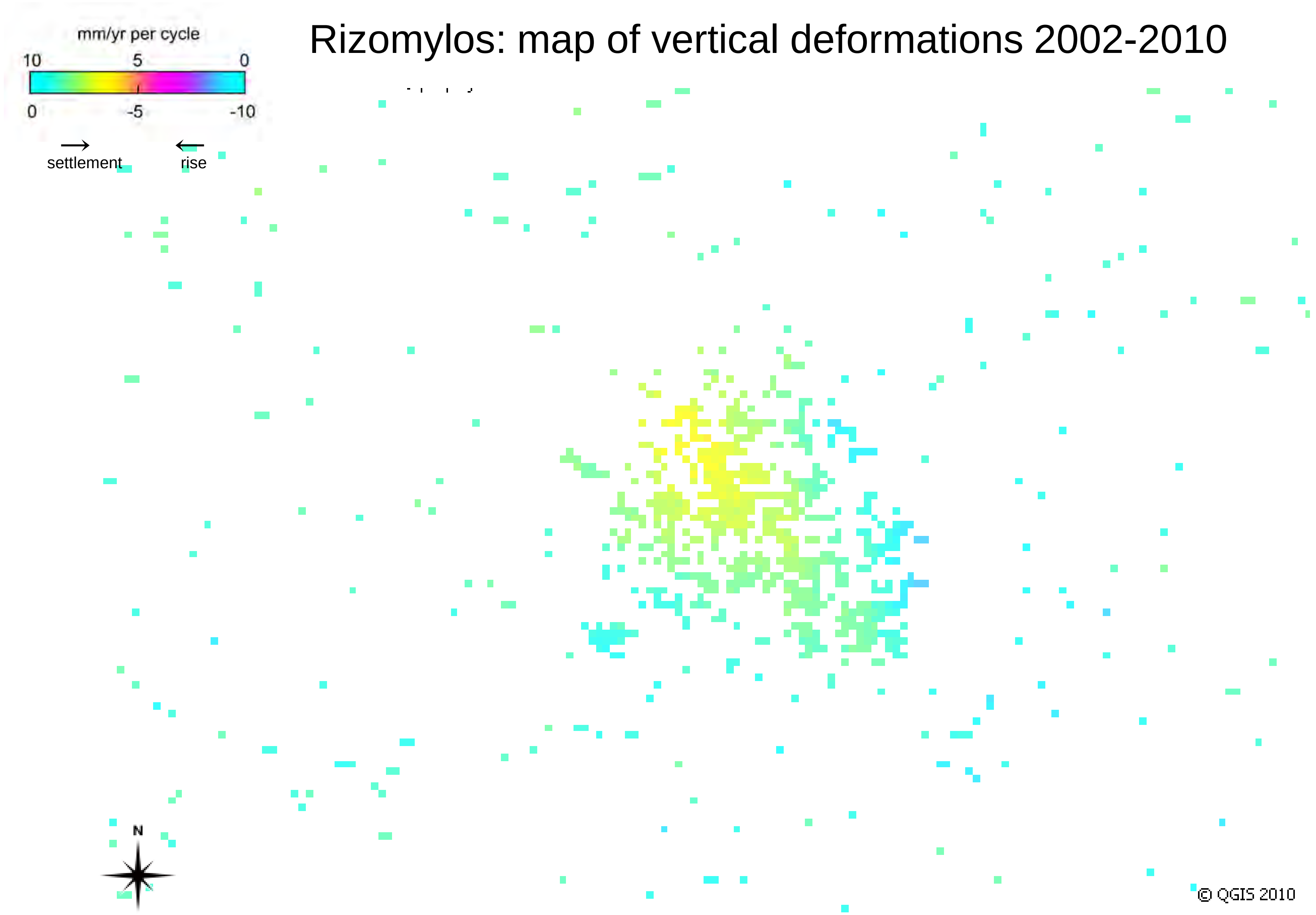
Karla region: map of vertical deformations 2002-2010



Rizomylos: map of vertical deformations 1992-2000



Rizomylos: map of vertical deformations 2002-2010



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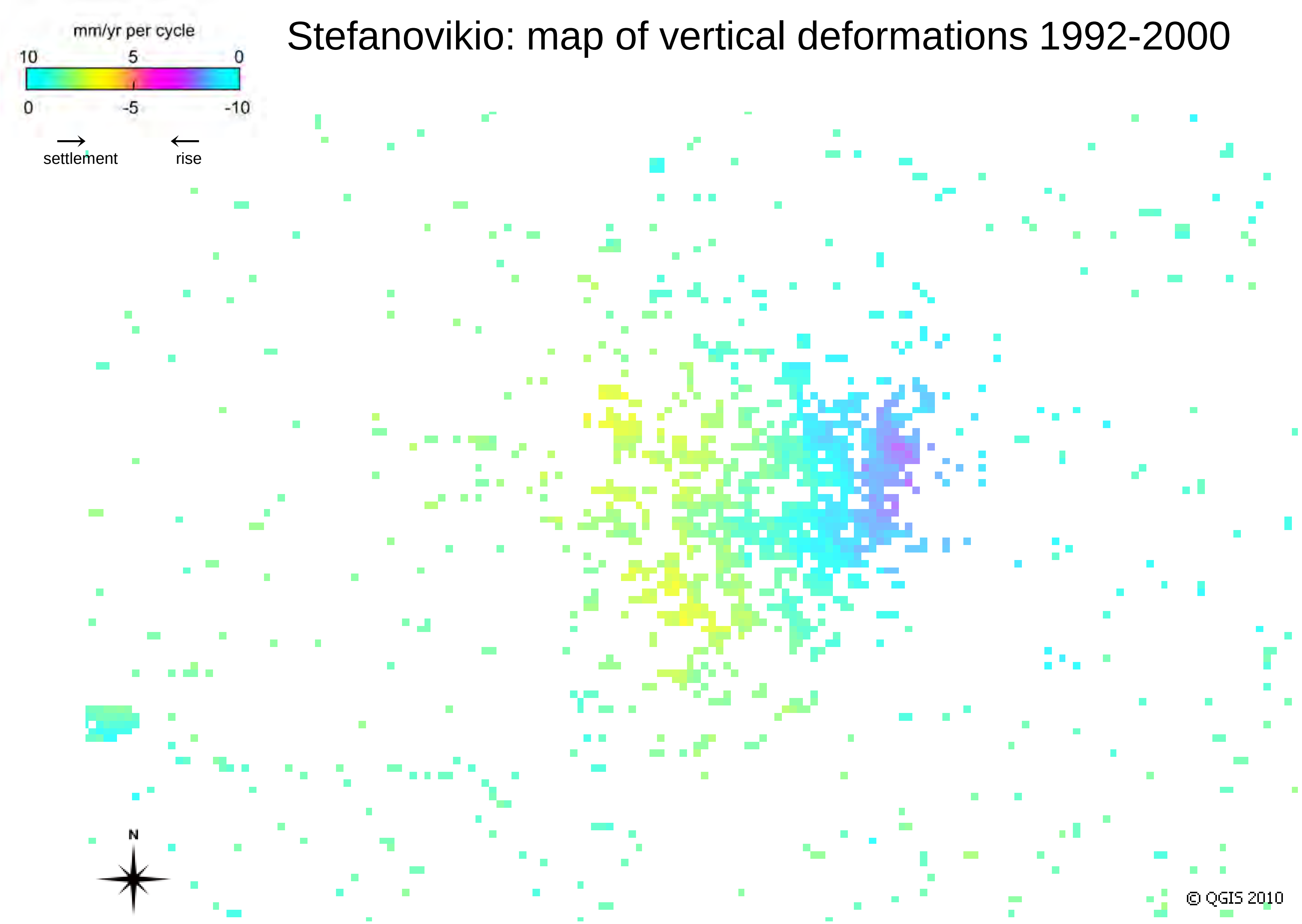
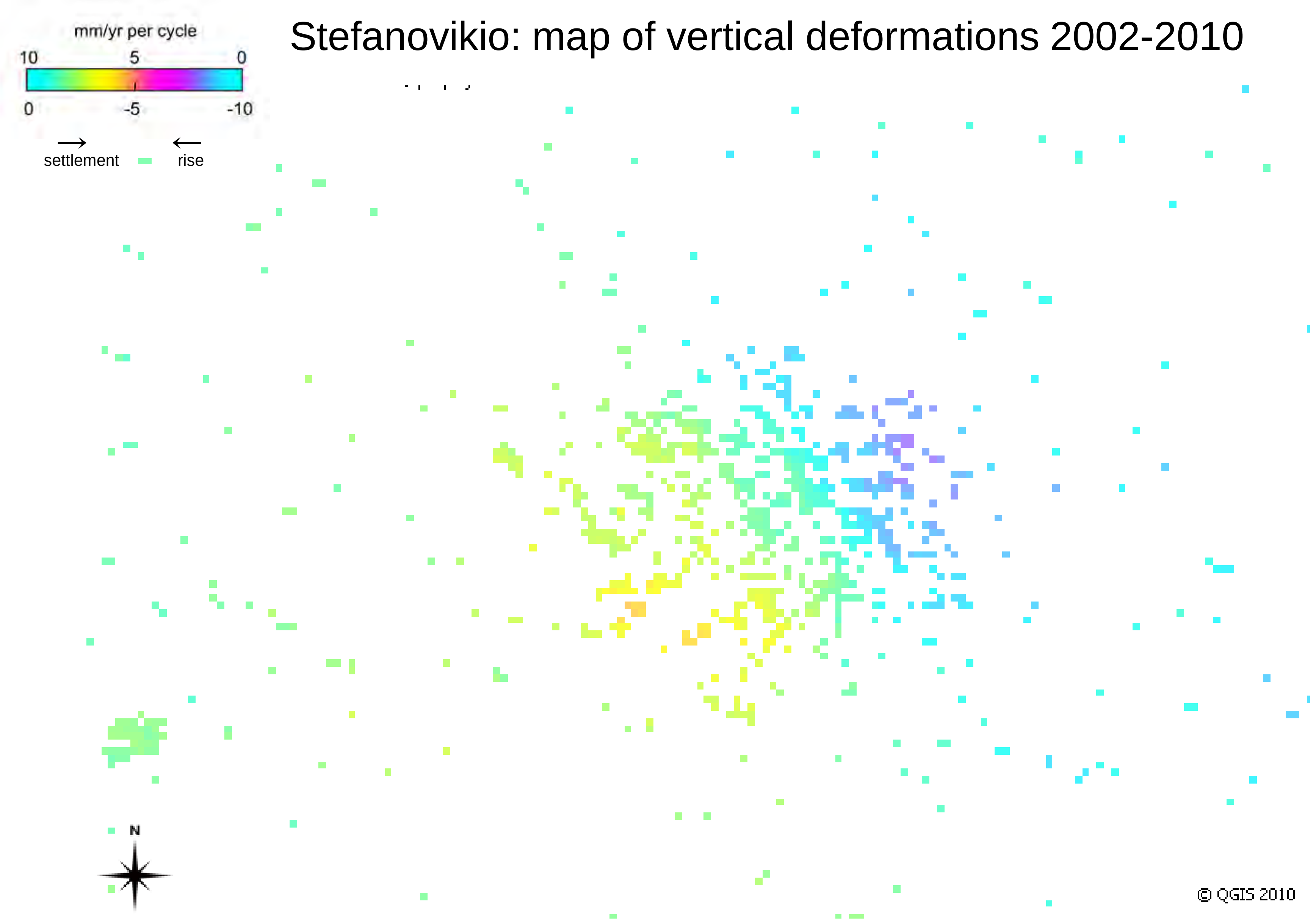
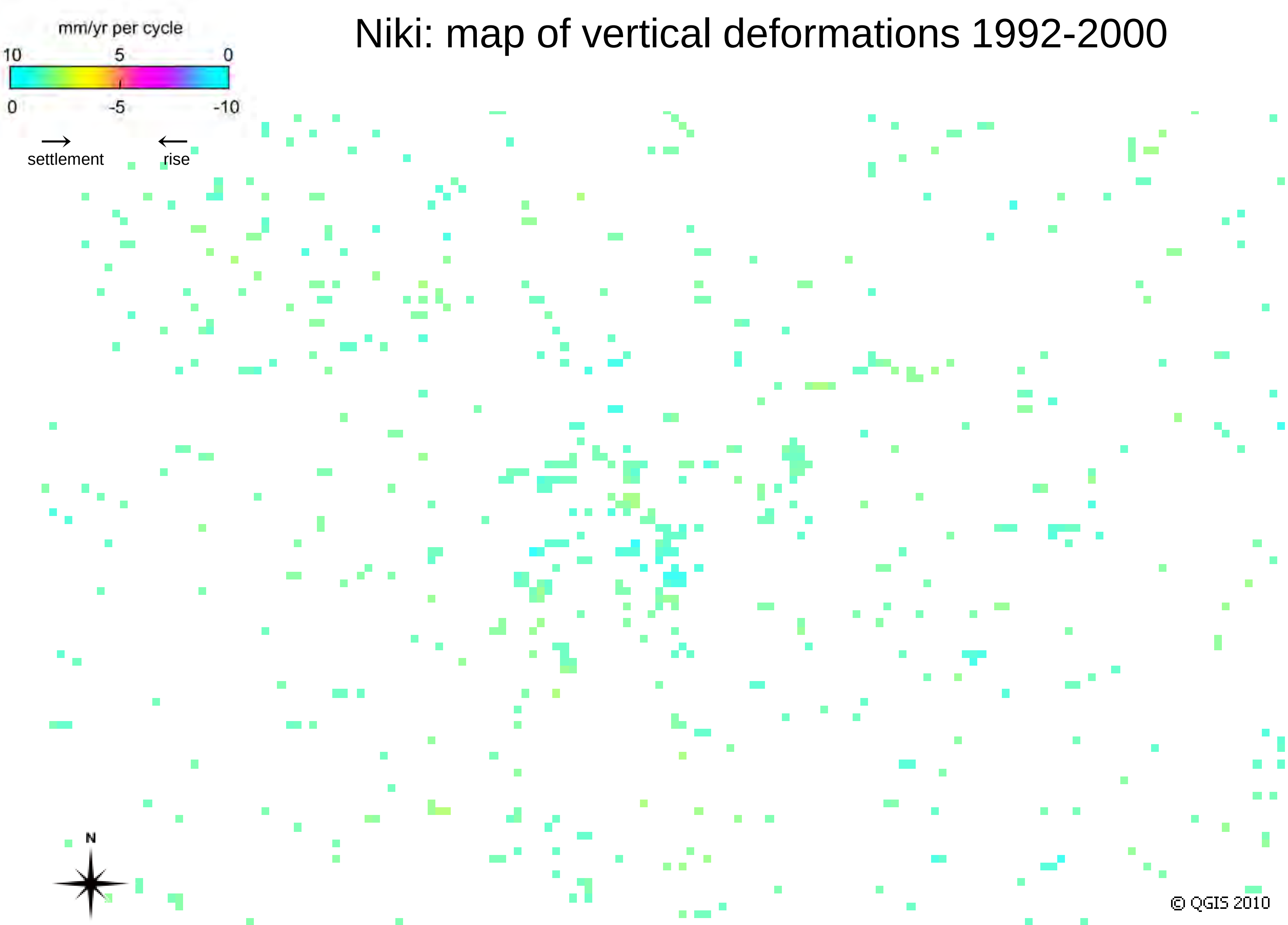
Stefanovikio: map of vertical deformations 1992-2000



Stefanovikio: map of vertical deformations 2002-2010



Niki: map of vertical deformations 1992-2000



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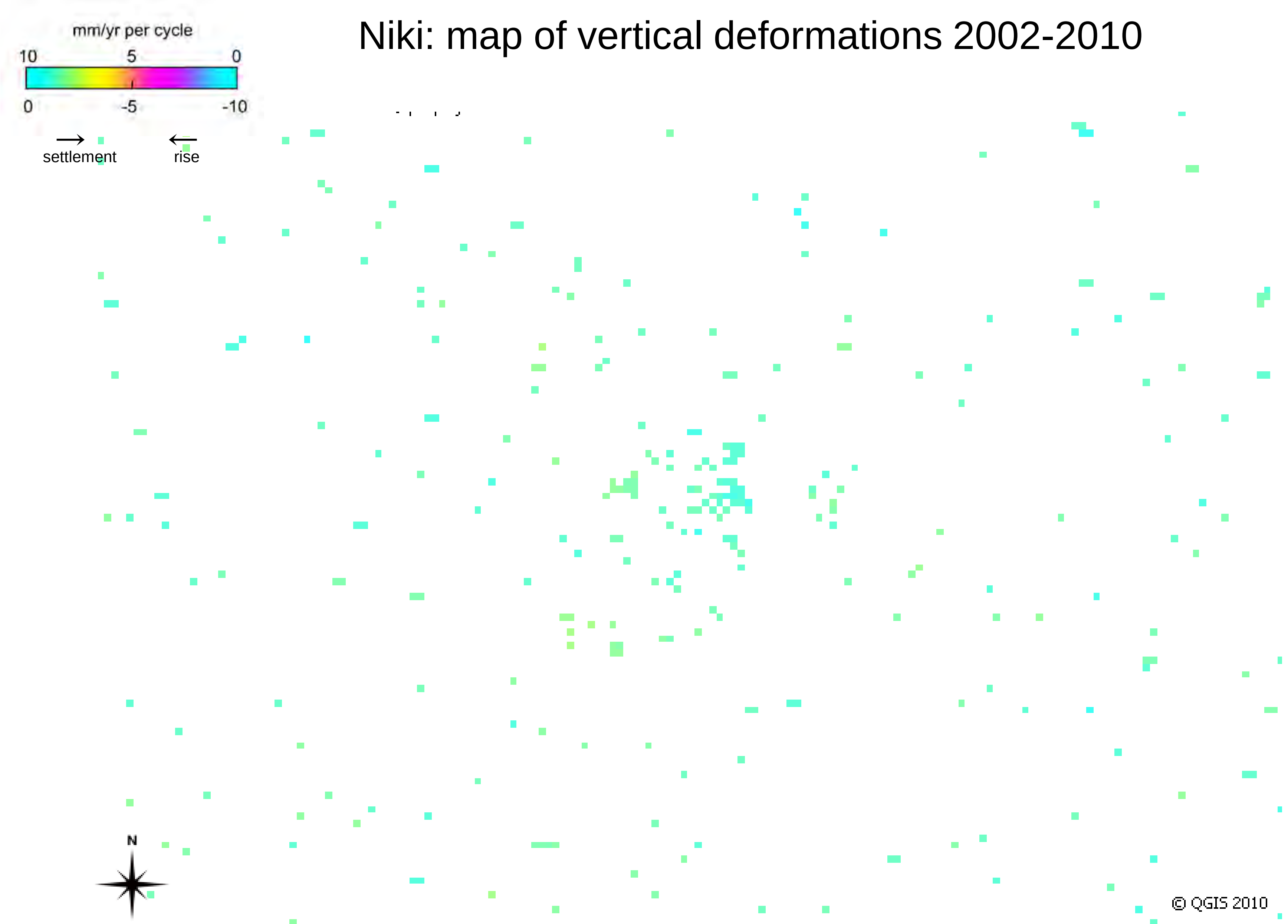
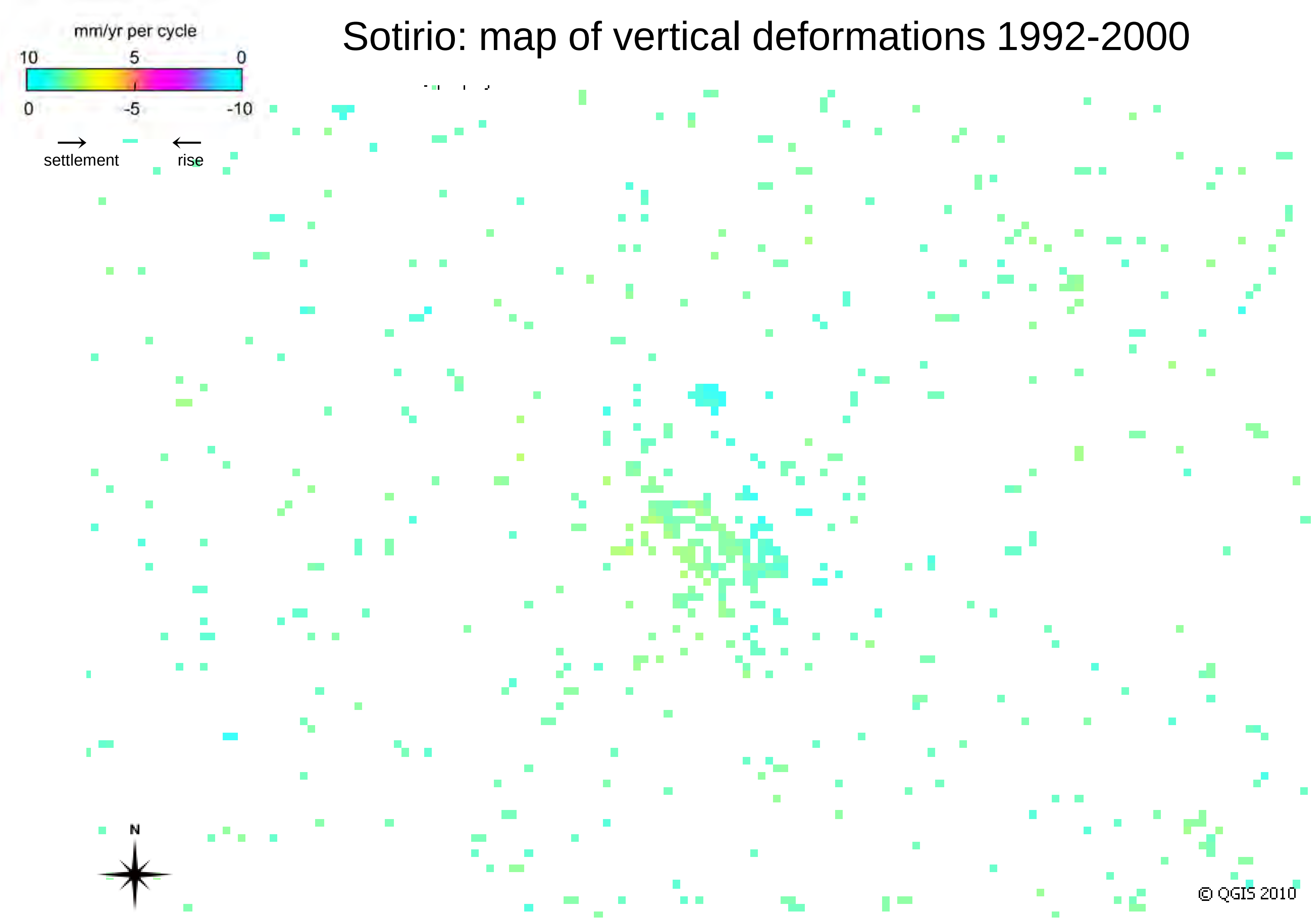
Niki: map of vertical deformations 2002-2010



Sotirio: map of vertical deformations 1992-2000



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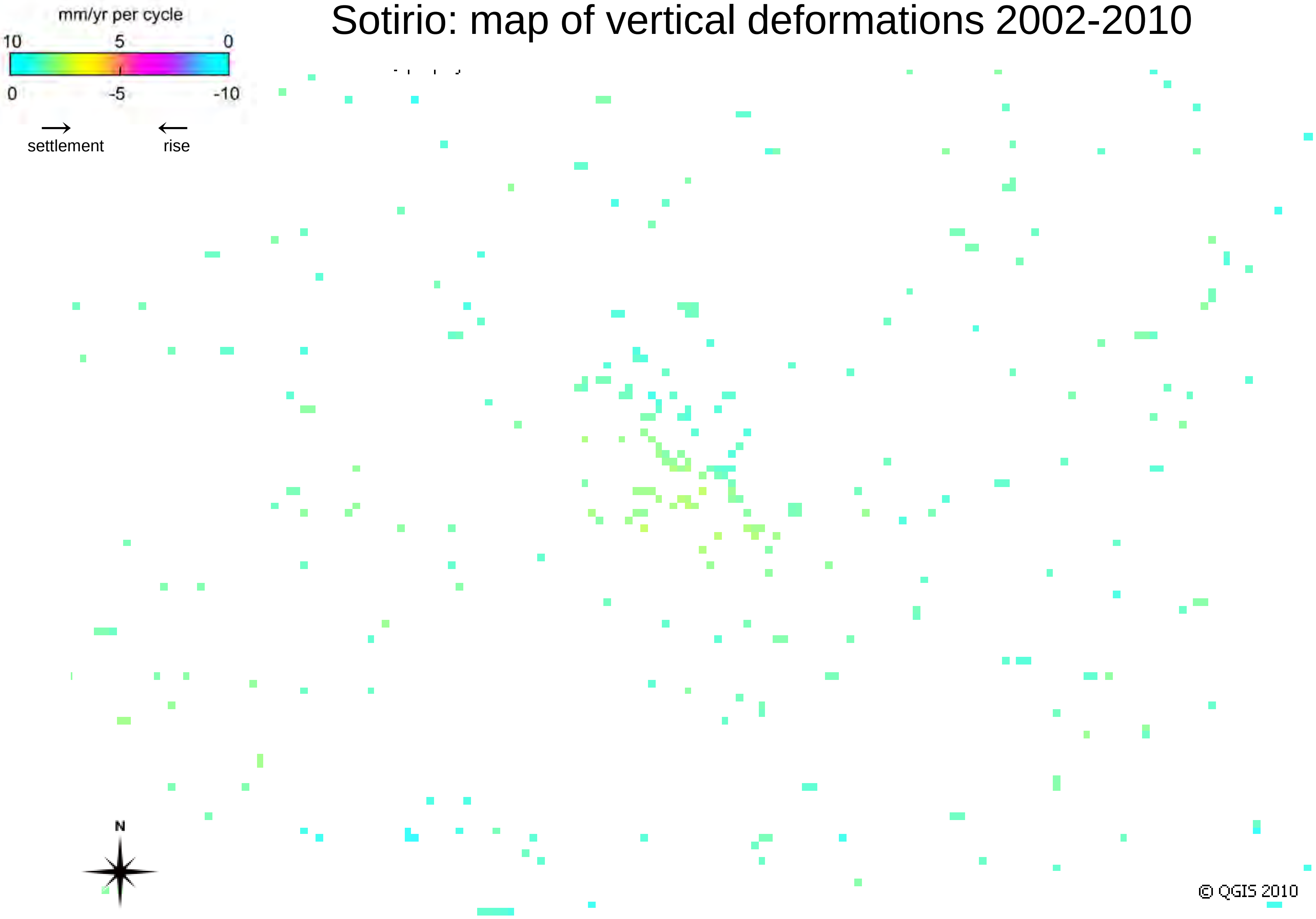
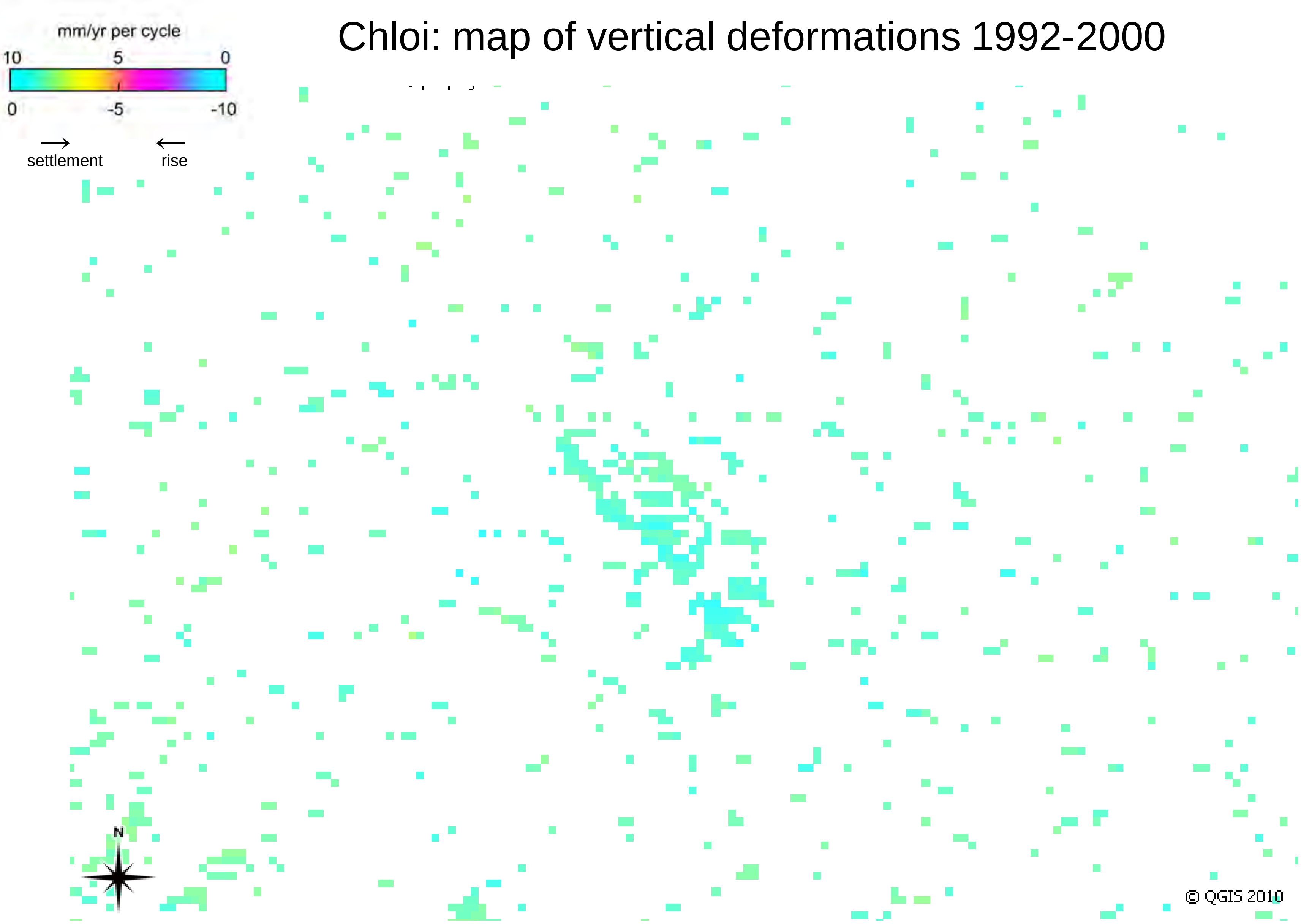
Sotirio: map of vertical deformations 2002-2010



Chloi: map of vertical deformations 1992-2000



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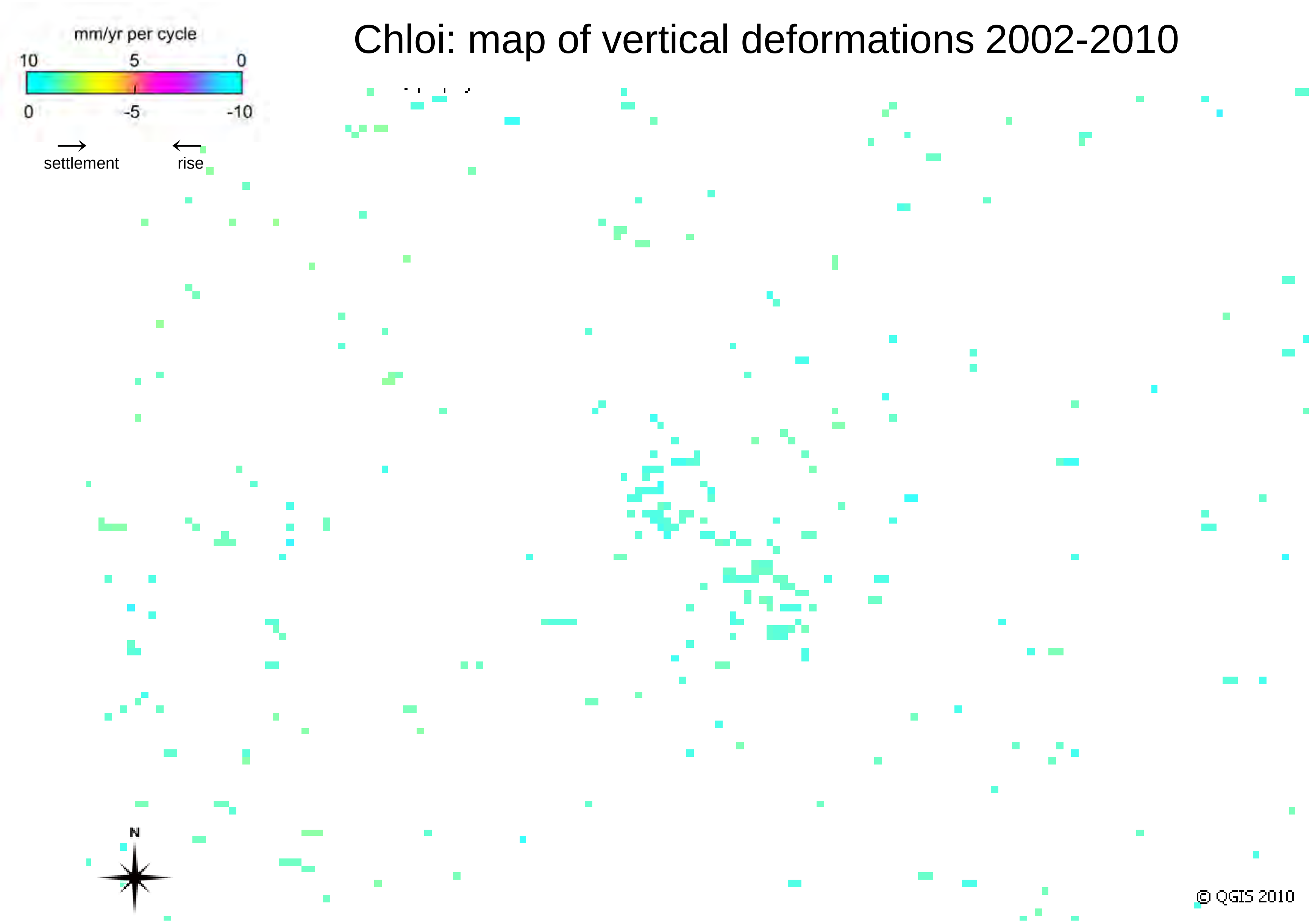
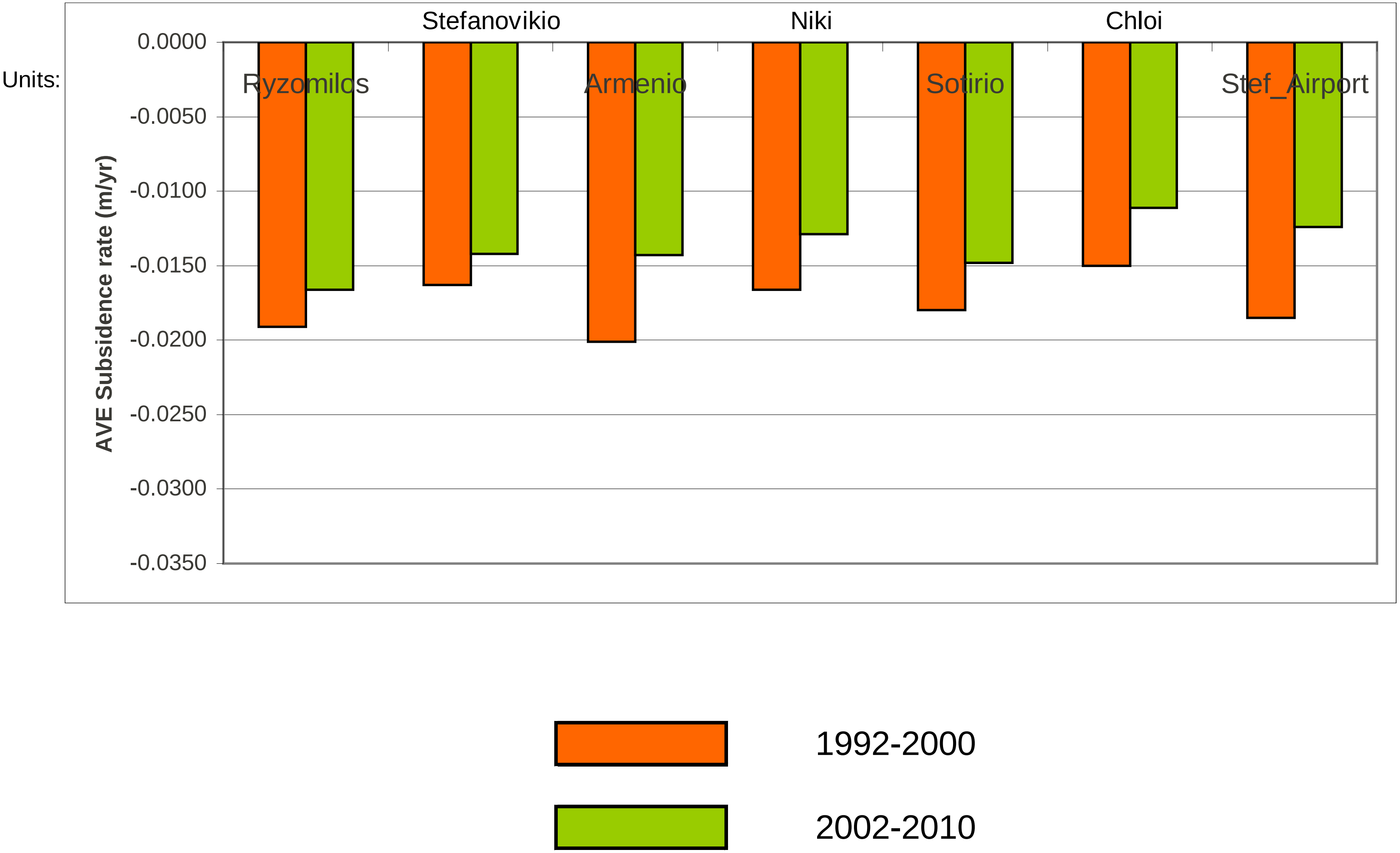
Chloi: map of vertical deformations 2002-2010



Average subsidence rate per year for the periods 1992-2000, 2002-2010 for different villages



Comparison of settlement computed by the geotechnical model and measured by radar technology is made to the 3 cases run by the geotechnical model program. It is observed reasonable agreement. It is observed that both methods predict lower settlement for Chloi. The model computed settlements are systematically bigger than satellite measurements by 40% to 60%

Area site	Satellite measured settlement (m)		Model computed settlement (m)	Settlement ratios	
W.Karla region	0.283		0.394	0.71	
Stefanovikio	0.274		0.427	0.64	
Chloi	0.235		0.377	0.62	

The principal reasons to the systematic deviation of results should lie within the computational model and its assumptions:

-The mathematical model is simplified

-There is a significant degree of uncertainty in the selection of geotechnical data that were scarce

On the other hand radar results are not final and may be improved. Particularly important is the temporal separation of differential interferograms processed. Not few difficulties were encountered in trying to apply existing methods to the Thessaly plain due to high magnitude of continuous deformations of the area.

CONCLUSIONS – FUTURE WORK

A geotechnical model was developed to predict settlements. With all uncertainties in the data, and limitations of assumptions of the equations employed, the model was found to give reasonable predictions. Model predictions were systematically above, by 40% to 60%, to those of satellite average measurements, results.

The model, corrected in terms of this systematic error, will be a viable method predicting future settlements of the region in terms of different water table change scenarios.

It is desirable that extensive on site measurements are collected to adequately validate satellite recorded measurements.