NATURAL RECENT EARTH SURFACE DISPLACEMENTS OF SAMBIA PENINSULA (BALTIC SEA COAST) STUDIED WITH PERSISTENT SCATTERERS INTERFEROMETRY

Zbigniew PERSKI [1)]* and Marek MRÓZ [2)]

[1)] *Polish Geological Institute – National Research Institute, Carpathian Branch, Skrzatow 1, 31-560 Cracow – Poland*
[2)] *Department of Photogrammetry and Remote Sensing, University of Warmia and Mazury in Olsztyn, 1, Oczapowski Street, 10-718 Olsztyn – Poland*
**Corresponding author's e-mail:* zbigniew.perski@pgi.gov.pl

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ABSTRACT
The paper describes the results of Persistent Scatterers Interferometry (PSI) study of Sambia peninsula. The idea of this work was to verify the hypothesis whether any terrain surface deformation that occur in Sambia area, could be interpreted as related to tectonic processes. Moreover, if any movements are detected what is their relationship to the 21 September 2004 earthquake? To answer these questions SAR (Synthetic Aperture Radar) data from European satellites ERS-1 and ERS-2 acquired from 1992 to 2001 were processed with interferometric techniques to archive independent data about terrain surface deformation. The obtained results – 4 sets of PS (Persistent Scatterers) points with calculated movement velocities (mm/yr) according to linear model were compared with published results of terrestrial measurements. The analysis of PS results confirms the occurrence of terrain deformations of tectonic origin of few mm/yr. The distribution of deformation velocities suggest its relationship to the recent activity occurring along two E-W trending seismoactive sub-zones located along Pregola river valley and possibly in the northern coast of Sambia Peninsula.

KEYWORDS: SAR Interferometry, Persistent Scatterers Interferometry, seismoactive zones, Kaliningrad earthquake

1. INTRODUCTION – THE EXCEPTIONAL KALININGRAD EARTHQUAKE

Sambia peninsula was considered as a seismically quiet region and therefore the earthquakes occurred on September 21, 2004 in the territory of Russian Kaliningrad enclave concerned big attention of seismologists and mass media. According to seismological records it was not a single event but two quakes occurred on 11:05 UTC and 13:32 UTC followed by a fairly large aftershock recorded 4 minutes later (Gregersen et al., 2007). There were several other small aftershocks that were felt, though not recorded instrumentally. The magnitudes of the events were about 5.0 and 5.3, respectively, which makes the two events one of the largest quakes noted in the 1000-year written history of the area (Nikonov et al., 2006; Nikonov, 2009, 2010a,b; Gregersen et al., 2007; Wiejacz et al., 2006). However, such magnitudes could be classified according to global Richter's scale as moderate events; their macroseismic evidences were very impressive. The two largest quakes were widely felt in Kaliningrad enclave, northern Poland, Lithuania, Estonia, Latvia and Finland. Surface vibrations were felt also far away, in eastern Denmark, Belarus, Norway and in high-rise buildings in St. Petersburg (Gregersen et al., 2007; Husebye and Mantyniemi, 2005; Ulomov et al., 2008). Many local damages and deformations associated with the earthquakes were recorded like e.g. ground cracks, railway and riverbed collapses and failures of the open pits edges due to landsliding, small sinkholes. Good study of the local damages has been given by Nikonov (Nikonov, 2011). The earthquakes caused minor damages to the buildings in Kaliningrad enclave and also in northern Poland (Assinovskaya and Gorshkov, 2005; Gregersen et al., 2007; Nikonov, 2005, Nikonov et. al., 2006; Nikonov, 2010b).

Due to exceptional character of Kaliningrad earthquakes the authors decided to study a potential earth surface deformations associated with the seismic event with spaceborne SAR (Synthetic Aperture Radar) interferometry. Unfortunately, due to lack of SAR data acquisitions of small temporal baseline – i.e. acquired just before and just after the earthquake such "classical" study was impossible. However, thanks to big data archive from European satellites ERS-1 and ERS-2 it becomes possible to check whether any measurable deformations in southern part of Sambia peninsula could be detected during 8-years period prior to the earthquake. The presented paper is summarizing the results of that study.

2. GEOLOGY AND GEODYNAMICS OF SAMBIA PENINSULA

Kaliningrad region is located at the margin of the East European Platform (EEP) and between two major Precambrian shields in Europe, i.e. Ukrainian Shield and Baltic Shield. The basement of Sambia peninsula belongs to West Lithuanian Granulite domain (Husebye and Mantyniemi, 2005) and is composed by alternating belts of metamorphic rocks of amphibolite and granulite phaces. The basement rocks are covered by Paleo-Proterozoic sediments and young Quaternary sediments. The sedimentary cover of Kaliningrad area is relatively thin, having 0.5 to 2.5 km total thickness (Nikonov et al., 2009).

Neogeodynamically, according to the map of the vertical movements since the beginning of Rupelian stage (Ludwig, 2003), the Sambia peninsula remains stable. However, the authors of the map draw the faults bounding Sambia peninsula along the northern and southern coasts (Fig. 1). These faults has been described as the Kaliningrad-Lithuanian potentially seismoactive zone by Aizberg at al. (1999). According to these authors the zone is the western continuation of the large Kurzem-Polotsk faults zone and includes three subzones: northern, central and southern. Within the area of Sambia Peninsula central and southern subzones are located. Central subzone was described as a small-amplitude rupture displacement associated with the regional active fault controlling the linear relief features. According to geological and geophysical data the structure is present in the basement and cover sediments and it corresponds to a maximum magnitudes of Mmax = 4.0 with minimum depth to the earthquake focus H = 5 km. The southern subzone consists of two latitudinal faults also determined from geological and geophysical data. The considered faults are situated in a zone of rather strong neotectonic deformations and therefore the subzone was classified as active with corresponding values of Mmax = 4.0; H = 5 km (Aizberg et al., 1999).

The main neogeodynamical feature of northern Europe is the postglacial uplift in Fennoscandia. Sambia peninsula and southern Baltic coast are located in its marginal zone where vertical deformations are close to zero. A good review of this neotectonic feature was given by (Fjeldskaar et al., 2000). According to the model presented by Gudmundsson (1999) the marginal zones of postglacial uplift are affected by compressional stress fields and therefore strike-slip and reverse faulting may occur. Similar conception was derived by Gründhal (2003) who analyzed directions of recent maximal stress of Central Europe. The Kaliningrad area, Baltic countries and NE Poland should be regarded as a transitional zone between the stress province of EEP and the Fennoscandian stress province. Most of stress indicators of this area infer an E-W directed compression (Fig. 1). The same stress direction within Kaliningrad area was earlier reported by Sim et al. (1995).

Recent terrain deformations within Sambia area have been measured with leveling techniques and derived from sea level variations measured by mareograph stations in Svetlogorsk, Pioneer, Baltijsk and Kaliningrad (Nikonov et al., 2009). According to short term mareographs record Sambia peninsula is uplifting from +1.1 mm/yr in the north to 3.9 mm/yr in the south (Fig. 1). Unfortunately main part of the repeated leveling line was parallel to E-W direction and therefore parallel to seismoactive zones. The velocities obtained by leveling show similar values to mareograph data. However, several anomalies have been noted and described as the zones of contrast movements (Nikonov et al., 2009). The locations of anomalies agree very well with the general trace of southern seismoactive sub-zone. According to the values of recent movement velocities the Sambia peninsula is affected by gradual subsidence that occurring westward and southwestward (Nikonov et al., 2009).

3. SEISMICITY OF SAMBIA AREA

The region of Sambia peninsula was considered as not seismically active and no seismic processed have been studied. Nikonov (2008) compiled the first catalogue of the earthquakes for this region paying special attention to eliminate all events of anthropogenic origin and also non-tectonic frost earthquakes (Nikonov, 2010a). According to this author, over the period of 1990-2006 the seismic activity was increased in 1995 and 2004 with tendency to southward spatial migration.

The epicenter locations of 21 September 2004 earthquakes according to available instrumental data have been calculated by different authors. All these estimates differ significantly since the nearest seismic station was located in Suwałki in Poland, some 220 km away. Early estimates presented by Wiejacz (2004) suggest that the epicenters of both main shocks were located offshore, close to southwestern coast near Baltijsk town. According to Nikonov (2006) the epicenters of two main shocks were located at the sea bottom, but close to northern and western coast of Sambia. Epicenters calculated by Husebye and Mantyniemi (2005) are locating the earthquake close to the center of the peninsula. Good reviews of different epicenter locations was given by Gregersen et al. (2007) and Aleshin et al. (2007, 2009). All analysis emphasizing that instrumental data and macroseismic fields are significantly diverges. According to macroseismic observations (Assinovskaya and Ovsov, 2008) which are more consistent than instrumental data, the highest intensity was noted in northwestern edge of Sambia peninsula (Fig. 2). However, more detailed maps of macroseismic effects were presented by Nikonov (2006, 2010b), Nikonov et al. (2007).

The focal mechanisms of the two main shocks was calculated by moment tensor inversion by tree seismological centers Harvard's, INGV's, ETHZ and

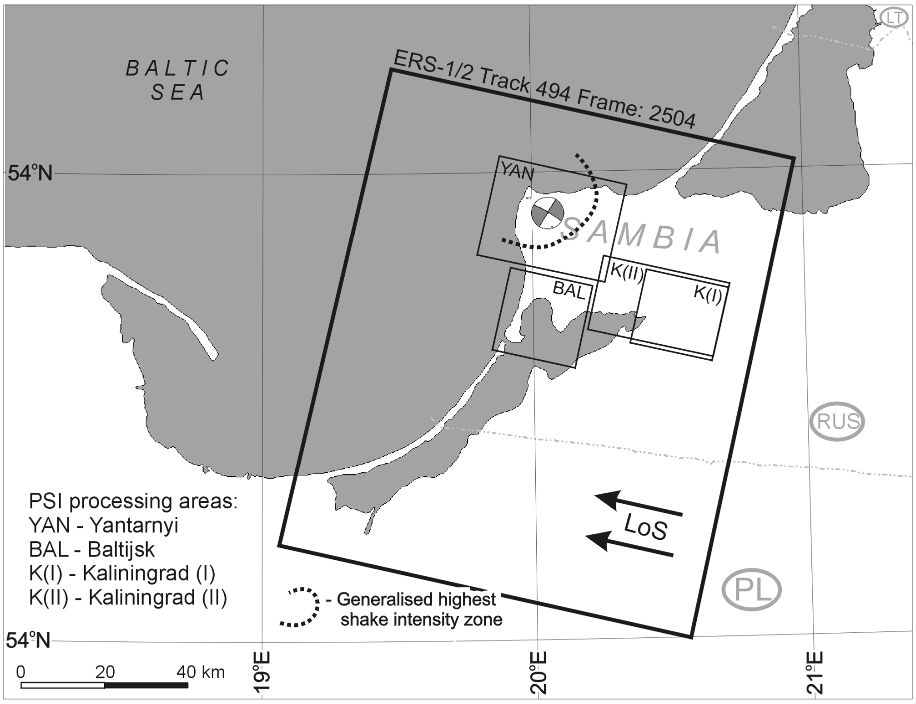

Fig. 2 Location map of study areas within Sambia peninsula (Russian enclave of Kaliningrad). Source mechanism diagram (Gregersen et al., 2007) according to Polish Institute of Geophysics (IGF) of the second bigger Kaliningrad earthquake. Location of the diagram does not indicate exact position of the epicenter. LoS - Line of Sight of radar beam

IGF's (Gregersen et al., 2007; Wiejacz 2006; Wiejacz et al., 2006). Despite methodological differences they present similar pattern with dominating strike-slip mechanism (Fig. 2). The first shock is interpreted as caused by a strike slip of about 120 degree strike – with displacement of the southwestern side towards the northwest in respect to the north-eastern side of the fault (right lateral) and the second shock as caused by a strike slip displacement along N-S trending left lateral fault (Nikonov, 2006; Aleshin et al., 2007, 2009).

September 21 earthquake caused probably also regional vertical displacement of Sambia peninsula. Nikonov and Enman (2007) analyzed sea level variations and meteorological observations of September 2004 and found irreversible rise of sea level that cannot be explained by weather variations. They concluded that most probably, entire Sambia peninsula subsided tectonically by 25-30 cm before the earthquake.

4. METHODS OF THE STUDY

The measurements of natural terrain deformations are from technical viewpoint very difficult, time consuming and expensive. Moreover, for reliable results the measurements need to be done repeatedly over many years. InSAR (Synthetic Aperture Radar Interferometry) is one of the new techniques for the measurements of subtle, very slow movements which may indicate the increment of seismic risk.

InSAR is a remote-sensing method that provides information related to the topography of the Earth's surface (Goldstein et al., 1988). It uses the phase difference between the radar signals from repeated SAR (Synthetic Aperture Radar) observations of the same area. The result of this operation is known as an interferogram, presenting relative phase differences 'wrapped' within 2Π radians. With further digital processing it is possible to reconstruct the full unambiguous signal by applying phase unwrapping techniques (Ghiglia and Pritt, 1998). First interferometric studies, focused on topography retrieval, demonstrated the applicability of InSAR to digital elevation model generation (Ferretti et al., 1997). Other approach represents the Differential InSAR (D-InSAR) that exploits the temporal baseline between consequent SAR acquisitions to derive phase differences which correspond with terrain displacements. D-InSAR has already been successfully used in different applications: the monitoring of volcanic activity, earthquakes, glacier dynamics, landslides and urban subsidence. In many cases D-InSAR has demonstrated its capability in measuring surface movements of the order of centimeters. A good overview of D-InSAR technique and its applications was given by Bamler and Hartl (1998), Massonnet and Feigl (1998), Rosen et al. (2000) and Hanssen (2001). The main problem associated with D-InSAR was related to the temporal decorrelation, due to changes in the electromagnetic properties and/or relative positions of scatterers within a resolution cell. Moreover, D-InSAR was very sensitive to atmospheric signal delay. The variable water vapor distribution related to the turbulent character of the atmosphere creates an additional phase contribution (Hanssen et al., 2006). For a single interferogram, this atmospheric phase screen (APS) is impossible to remove and therefore the accuracy of measuring small deformations is significantly reduced. Due to those properties the operational use of D-InSAR is limited to a) short temporal baselines, b) phenomena with strong deformation gradient in respect to radar wavelength within the acquisitions, c) areas with limited vegetation, and d) advantageous weather conditions during master and slave acquisitions.

To bypass the limitations mentioned above, point wise InSAR techniques have been developed; see e.g. Ferretti et al. (2000, 2001). The initial method developed by POLIMI used radar point targets as 'natural' corner reflectors (i.e. corners of the buildings, walls, poles, fences, rocks etc.). The phase of such targets (labeled as Persistent Scatterers, or PS) is not sensitive to small incidence angle variations and temporal decorrelation. The techniques are labeled as PSI – Persistent Scatterers Interferometry. Fundamental in PSI methods is the exploration of SAR data archives and use of all available SAR images (typically more than 20 acquisitions) acquired from the same geometry by coregistering and resampling them to the same master SAR scene. After the coregistration of all slave images to the master, interferograms are computed with D-InSAR technique. Later, the time series of interferometric phase are decomposed into (linear) deformation, topography (relative height) and APS. The crucial element in the PSI analysis is the identification of potentially coherent points. The first selection might be based on amplitude dispersion as in the original PSI algorithm (Ferretti et al., 2001) or coherence as in case of SBAS or StaMPS (Hooper et al., 2004). Redundant observations are consecutively used to estimate the APS and the (linear) deformation. This estimation is based on observation that APS is strongly correlated in space but not in time whereas deformation is usually strongly correlated in time (Colesanti et al., 2003).

PSI techniques have also some limitations that need to be noted. Similarly to InSAR technique the PSI is capable only to measure path differences in its Line of Sight (LoS) direction. Therefore, having only the projection of three-dimensional displacement to the radar LoS, it is not possible to retrieve the actual displacement vector. To properly decompose the displacement into horizontal and vertical components the InSAR measurements taken from two directions (ascending and descending interferograms) should be combined. For the third component, assumptions or the measurements taken by other techniques are necessary. Unfortunately within this study only data acquired from single direction (descending satellite pass) were available therefore all results presents LoS velocities. The main uncertainties associated with PSInSAR method are related to the proper phase unwrapping. In most cases the phase unwrapping errors are associated with low density networks of PS candidates (PSCs) and too long arcs. For non-linear deformations the phase component associated with the deformation signal might be mixed with atmospheric component.

In case of slow tectonic deformations and observation data from 8-years period the linear model appears to be good approximation. All PSI measurements are relative in space and in time. As the temporal reference the master SAR acquisition is used. The spatial reference consists of one of PS candidates for which all the components are assumed to be zero. This PS point is used as a reference for further adjustment of PSCs network. Having all these limitations in mind, the results of PSI processing must be very carefully analyzed and interpreted. In most cases proper interpretation is impossible without in-depth knowledge about PSI processing part.

5. RESULTS AND INTERPRETATION

For PSI processing the TU Delft implementation (Leijen et al., 2005) of original Persistent Scatterers algorithm (Ferretti et al., 2001, 2000) was applied. For D-InSAR part of the processing the Delft Object Oriented Interferometric Software (DORIS) was used (Kampes et al., 2003). In order to spatially analyze the PSI results and compare them with other data, the GIS (Geographic Information System) environment was applied. GIS allows combining all interferometric results and external data into one common reference system. For this purpose open-source GRASS (Geographic Resources Analysis Support System) was used (GRASS-Development-Team, 2006).

The interferometric processing for the study area was performed based on SAR images acquired by European satellites ERS-1 and ERS-2. The images that covering almost 8-year period from 04 April 1992 to 11 January 2001 (57 SAR scenes) were acquired from the descending satellite track (Fig. 2). Due to technical reasons (mainly memory limitations) there was no possibility to process entire Sambia peninsula area. We focused therefore on 3 areas named based on main settlements: Kaliningrad, Baltijsk and Yantarnyi. For Kaliningrad area the processing was performed twice (Kaliningrad I and Kaliningrad II) – applying different settings. Areas: Kaliningrad and Yantarnyi are located along southern seismoactive sub-zone. Yantarnyi area is covering NW edge of the peninsula where northern sub-zone was located. This area was also affected by the strongest macroseismic effects of

Table 1 Basic parameters of two independent PSI sets of Kaliningrad area.

	Kaliningrad (I)	Kaliningrad (II)
Size of processed area (cols x rows)	1800 x 9000	2800 x 9000
Center of the area (Lat./Lon.)	54.6893576N / 20.5352465	54.7102920N / 20.4541037E
Number of interferograms	59	34
Temporal reference (acq. date)	03-FEB-1997	14-APR-1997
Reference point (Lat./Lon.)	54.734531N / 20.540207E	54.723892N / 20.538801E

Table 2 Statistical parameters calculated for PS linear velocities for northern (N domain) and southern (S domain) parts of Kaliningrad city.

	Kaliningrad I		Kaliningrad II	
Statistical parameter	N domain	S domain	N domain	S domain
Number of PS points	16093	5760	3505	1039
Minimum	-5.96636	-5.97063	-5.93603	-5.92871
Maximum	2.89484	2.93514	2.9576	2.83903
Mean	-0.551805	-0.908318	-0.789407	-1.10712
Median	-0.402969	-0.825217	-0.586674	-0.945264
Mean difference	-0.356513		-0.317713	
Median difference	-0.422248		-0.35859	

both two earthquakes.

5.1. KALININGRAD (KRÓLEWIEC) AREA

As it was mentioned before, the Kaliningrad area was processed twice with PSI method. The second processing (Kaliningrad II) was performed for slightly larger area shifted eastward. Moreover for this case a different master scene has been used and different number of interferograms. For PSI processing the PSC network was constructed independently with different reference PSC (Table 1).

In both cases the same linear model was used for deformation estimation. A very high density of PS points was obtained for Kaliningrad city.

For Kaliningrad (I) it was: 147 PSC (PS Candidates) and 25 991 PS points. Obtained relative linear velocities (for the SAR observation period from 1992 to 2001 yr.) vary from -5 to +2 mm/year. However, it was found that the spatial pattern of PS velocities is very specific: Northern part of the City, north from Pregola River valley reveals relative uplift (1 – 2 mm/yr) whereas Southern part of the City presents relative subsidence of -1 to -2 mm/year. Such observation was confirmed later by PS point statistics. Therefore a set of PS points was divided into two domains along Pregola River valley and then separate statistical parameters were calculated. Very similar PS velocities distribution was obtained for independent processing of Kaliningrad II area (Table 2.).

Mean and median values differences calculated for two domains reveals the same relative movement between two zones of ~ 0.35 mm/year. According to the spatial distribution of PS velocity pattern and other data, there is no evidence of any artificial/hydro-geological phenomena that could explain such observation. Moreover, for both, independent PSI processing the obtained results are almost identical, therefore the result could not be explained as a processing or data artifact.

5.2. BALTIJSK AREA

For the Baltijsk area, due to its sparse urbanization, the total number of PS was much smaller than for Kalingrad (5118 PS points). The PS points were not uniformly distributed but grouped into few cluster related to individual settlement. Due to that PS points configuration where clusters are connected by long arcs with lower redundancy, the liability of these results is much lower. Therefore the results obtained for Primorsk and Svetly are not considered for quantitative interpretation. Best distribution of PS points is located near Baltijsk town and harbor facilities. This area reveals similar regularity as Kalingrad area: southern part is subsiding with respect to the northern part. The velocity contrast is much higher than Kaliningrad reaching almost 4 mm/year. It should be noted, that higher movement velocities in western part of Sambia were also reported by Nikonov et al. (2009).

5.3. YANTARNYI AREA

The northern coast of Sambia peninsula is very sparsely urbanised without big settlements and cities. The total number of 1493 PS points was obtained and the points are grouped in clusters that correspond to villages: Yantarnyi, Svetlogorsk and Pioneer. Majority of the points show deformation velocity close to zero. However, the group of points in Pioneer village located along the coast show relative uplift of +2 mm/yr. Similar effect was observed for the points

Table 3 Fault parameters used for surface deformation modelling.

Strike-slip displacement		Normal displacement	
strike:	84.000	strike:	84.000
dip:	90.000	dip:	90.000
rake:	0.000	rake:	-90.000
total slip(m):	0.010	total slip(m):	0.005
strike-slip component(m):	-0.010	strike-slip component(m):	-0.000
dip-slip component(m):	-0.000	dip-slip component(m):	0.005
depth to top(km):	0.500	depth to top(km):	0.500
depth to bottom(km):	10.000	depth to bottom(km):	10.000
fault length(km):	55.000	fault length(km):	55.000

located near the northern coast and in to Svetlogorsk in respect to Yantarnyi. However, it should be emphasized that the obtained deformation values were very small for small number of PS points but the values are rather uniformly distributed in space. The reasons of that relative uplift might be interpreted as related the recent activity of northern seismoactive sub-zone.

5.4. INTERPRETATION

Independent processing of different overlapping sub-areas and validation of the results allow concluding that presented deformation values are related to terrain movements and not to processing artifacts. Usually, the interpretation of PSI results is difficult because of different phenomena responsible for deformations: artificial (mining, tunneling, water withdrawal), natural non-tectonic (karst, alluvial sediments compaction, peat decomposition), natural tectonic (salt tectonic, faulting, and folding). In Sambia peninsula there is no significant mining activity occurring that might have influence on the results. The alluvial sediments compaction is expected in Pregola river valley in Kaliningrad city. However, the urbanized area of Kaliningrad is only partially located on alluvial sediments that might be subjected to compaction. Therefore the boundary of the Pregola river valley should be visible in deformation values. The PS points located within the valley does not show any significant difference to the PS located outside the valley and thus alluvial compaction phenomena does not explain the obtained deformations. Consequently, the observed relative displacements should be interpreted as results of tectonic processes.

Unfortunately, at this stage of research we cannot fully interpret the movement as vertical or horizontal. All PSI measurements were taken along LoS (line of Sight) vector, which is the line of radar signal propagation towards to earth. In a case of ERS satellites LoS vector (Fig. 2) is almost vertical (23^{o} from the nadir). Having only one component it is not possible to decompose the movement into X,Y,Z components (Wright et al., 2004). In case of Sambia, both types of the movements are possible: vertical movements are well documented by mareograph stations and leveling but 21 of September earthquake has horizontal stress pattern that indicates strike-slip activity.

Modelling of LoS surface displacement caused by both types of deformation occurring along Pregola river dislocation have been performed with Okada model that allows to calculate analytic solution for surface deformation due to shear and tensile faults in an elastic half-space (Okada, 1985). The resulted deformation patterns are presented in Figure 4 and fault parameters used for modelling are presented in Table 3.

The simplest, vertical fault was used assuming pure strike-slip or normal displacement along vertical rupture. The simulated rupture depth was assumed up to 10 km below the surface – i.e. the approximate depth of Kaliningrad earthquake hypocenter. However, to produce deformation at the surface similar to presented at PSI dataset different slip rates have been used, 0.01 m for strike slip and 0.005 m for normal displacement respectively.

According to displacement modelling (Fig. 4) and long term observations (levelling and mareographs), the pattern obtained with PSI fits better into vertical displacement model. However, this interpretation does not exclude possibility of strike-slip model earthquakes because according to crustal doming model (Gudmundsson, 1999) in the marginal zones of postglacial uplift both types of stresses are possible.

6. CONCLUSIONS

For the study area of Sambia peninsula the obtained results from 4 areas processed independently show quite uniform pattern. The points located south of Pregola river valley and in the Baltijsk area show relative subsidence (0.4 to 4 mm/yr) in respect to the points located in the northern part. Deformation velocities obtained at the northern coast suggest that the northern coast is uplifting of 1 to 2 mm/yr in respect to the centre of peninsula. The spatial distribution of PS velocities suggests that the boundaries between the zones of different velocities are parallel to the E-W direction. Data derived from PSI analysis present very similar velocities and their distribution as results obtained by terrestrial techniques like mareographs and repeated levelling (Nikonov et al., 2009). In author's opinion the obtained with PSI technique the Earth surface deformation velocity pattern should be interpreted as recent tectonic activity that occurs along known seismoactive zones, southern along Pregola river valley and northern, along Baltic Sea coast.

All the PSI measurement have been performed along LoS direction which is close (23 degrees from nadir) to the vertical. Therefore, after careful analysis all the velocities were interpreted as close to vertical subsidence and uplift.

Neogeodynamical activity of seismoactive zones bounding Sambia peninsula along its northern and southern coast is most probably related to stress accumulation occurring in the marginal zone of postglacial uplift of Fennoscandia.

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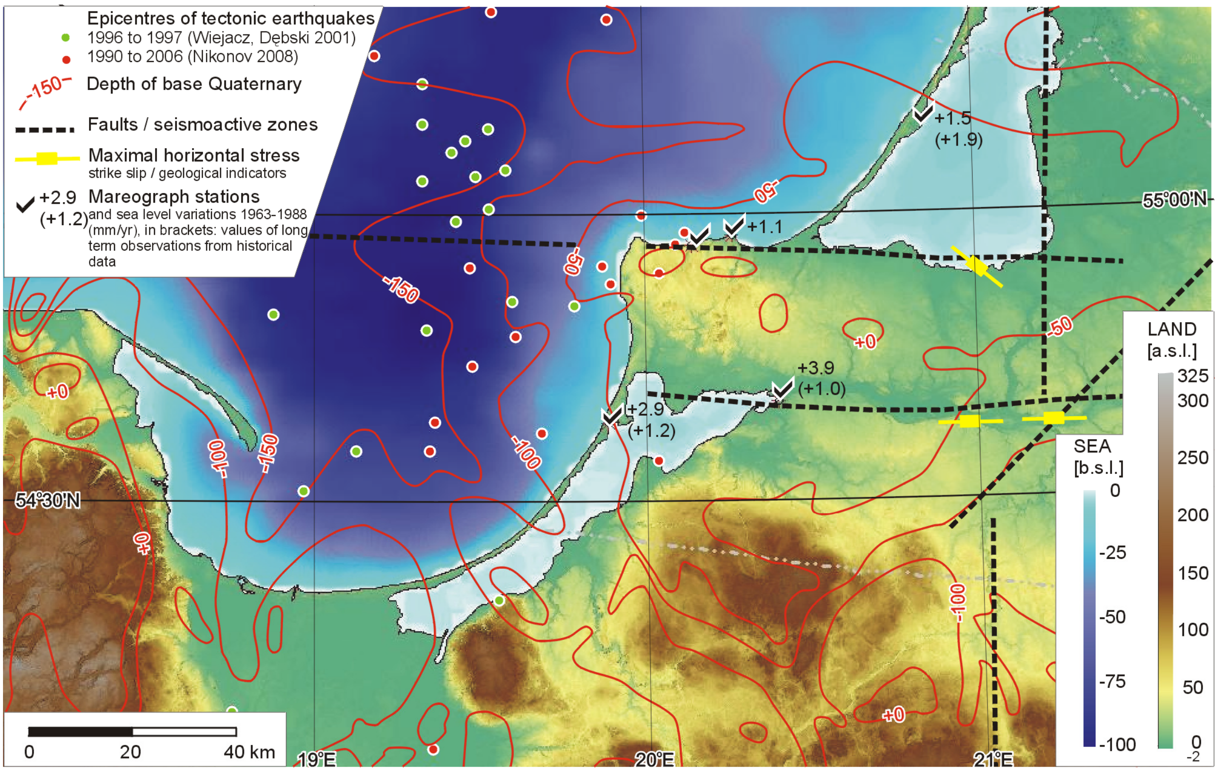

Fig. 1 Geodynamics of Sambia Peninsula. Compilation map based on different data sources: topography: DTED Level 2 and SRTM data, Baltic Sea bathymetry (Seifert et al., 2001), Depth of base quaternary (Ludwig, 2003), Earthquakes in Gulf Gdansk (Wiejacz and Dębski, 2001; Nikonov 2008), Maximal horizontal stress (Grünthal, 2003), Sea level variations at mareograph stations (Nikonov et al., 2009).

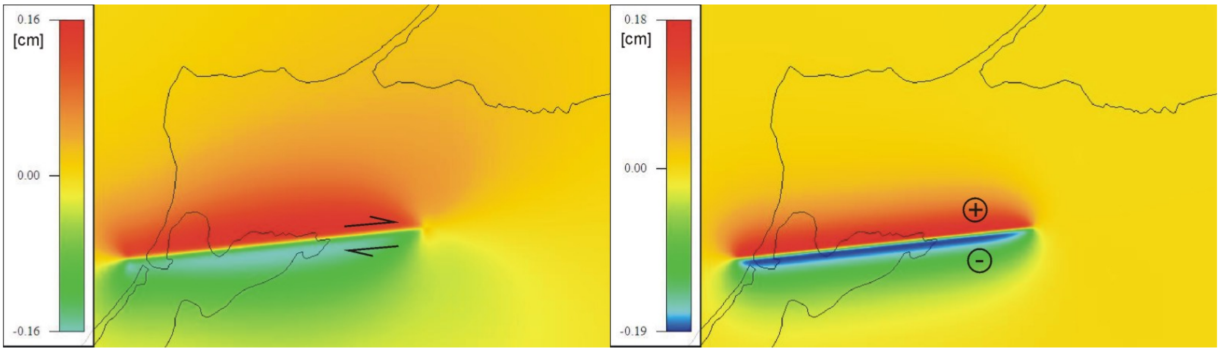

Fig. 4 Modelled LoS surface deformation caused by strike-slip (left) and normal (right) long-term (1992-2000) displacements of Kaliningrad segment of Kaliningrad-Lithuanian seismoactive zone. The location of the fault as interpreted from PSI data (Fig. 3).

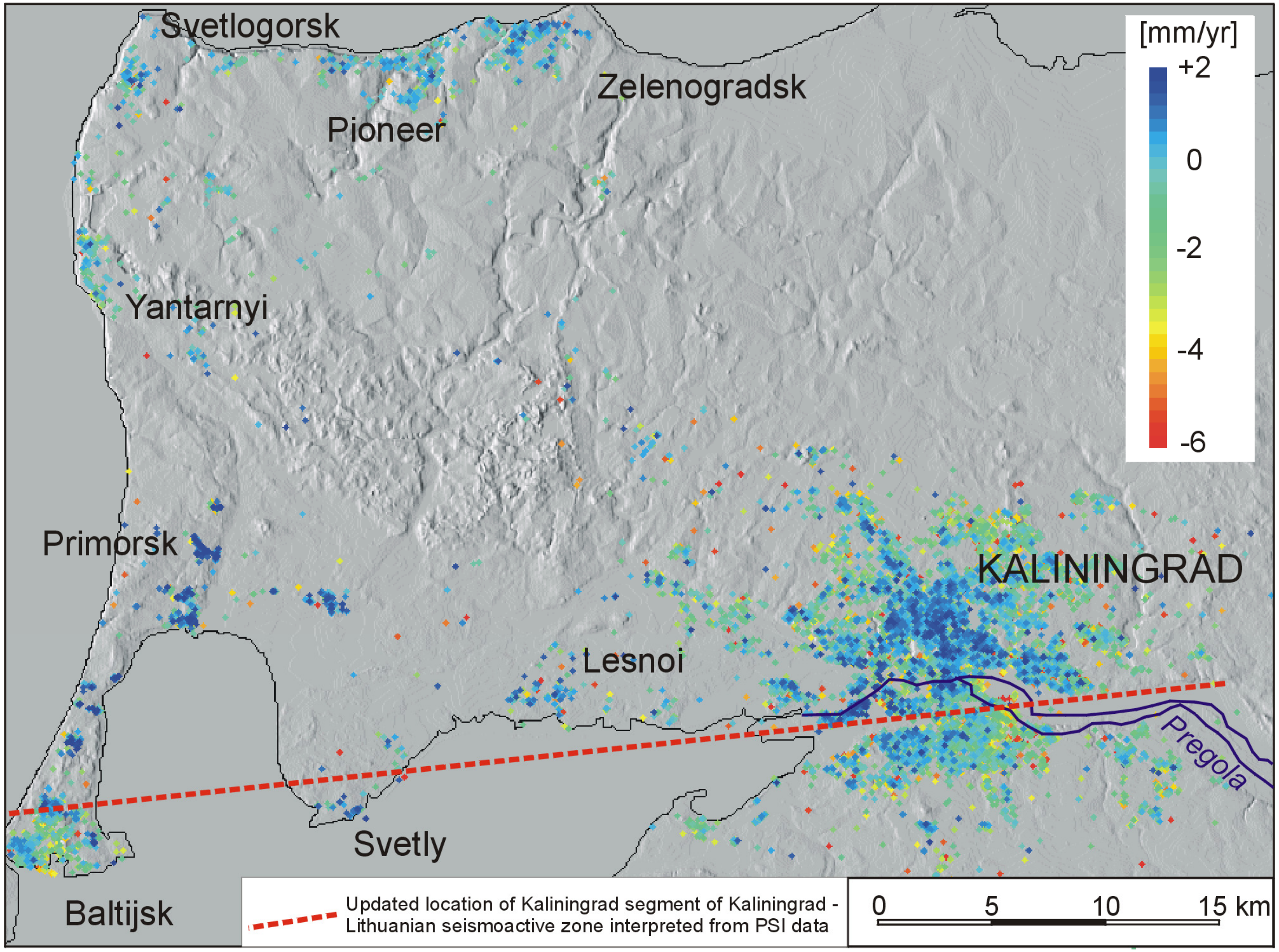

Fig. 3 Combined PSI results for Sambia peninsula. Linear velocity estimated from SAR data acquired from 1992 to 2001.