GPS network measurements in the Kárahnjúkar area in 2009

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Nordic Volcanological Center
Institute of Earth Sciences Report 1001
University of Iceland
September 1, 2010

1 Introduction

As a part of a monitoring and research program by Landsvirkjun in the Hálslón area, an extensive network for crustal deformation research was established there in 2005 by the Institute of Earth Sciences, University of Iceland. The network was initially measured in 2005 and then remeasured in August 2006, 2007 and 2008 (*Ófeigsson et al.*, 2005, 2006; *Ófeigsson*, 2008; *Ófeigsson et al.*, 2009). This report adds the results from a GPS campaign conducted in August 2009. A total of 35 benchmarks were occupied within a distance of 20 km from Kárahnjúkar. In addition we include results from measurments around Upptyppingar and Álftadalsdyngja.

The GPS network was established in order to monitor the effect of reservoir filling. Processes that have been detected as a possible consequence of the filling Hálslón reservoir include (14±10) mm of crustal sagging due to increased load during the initial filling and (39±6) mm of total widening across the northern end of Hálslón. The widening relates to dilation of fractures under the reservoir, as well as pressure on steep walls of the reservoir next to the Kárahnjúkar dam. Other crustal processes that have previously been detected are uplift associated with decreasing load of the nearby Vatnajökull ice cap as well as seasonal variations in the continuous GPS network (*Geirsson et al.*, 2006; *Grapenthin et al.*, 2006) which are attributed to the seasonal variations in the snow load on the three biggest glaciers.

2 Previous GPS measurements

Three GPS networks have been established in the Kárahnjúkar area. One with continuous GPS stations and two networks of benchmarks measured in campaigns. Together these three networks form a coherent monitoring network for detecting spatial and temporal variations in crustal movements at Kárahnjúkar.

In order to resolve temporal changes in the Hálslón area in real time and monitor seasonal variations, three continuously measuring GPS stations were installed in the area by the Icelandic Meteorological Office in 2004-2005. Station SAUD located at Sauðárháls was installed in October 30, 2004. Station KARV located near the camps at Kárahnjúkar was installed in September 17, 2005. Station BRUJ located near Brúarjökull was installed on September 16, 2005. Detailed information about the continuous GPS sites can be found on the website of the Icelandic Meteorological Office (IMO) (*Geirsson*, 2006). In the fall of 2007 station KARA was replaced by station INTA which is now maintained by the Meteorological Office. Additional 2 continuously running GPS stations HAHV and BALD, which were maintained by Hnit Consulting Engineers and the Engineering Research Institute of the University of Iceland, are now maintained by IMO.

Another network was also established in the Hálslón area by Hnit Ltd. and the Earthquake Engineering Research Centre of the University of Iceland. This network is confined to the area close to the dam sites and is focused on detecting fault movements in the immediate vicinity of the three dams (*Snæbjörnsson et al.*, 2006).

Our Kárahnjúkar GPS network consists of 35 benchmarks in the vicinity of

Hálslón. Most of the stations were installed and initially observed in August, 2005. In addition benchmarks located along the Kverkfjöll fissure swarm were included in the network. The data from these campaign measurements are analysed together with data from a number of continuous GPS stations (CGPS). Included in the processing were the CGPS stations REYK, HOFN, ISAK, SKRO, RHOF, AKUR, ARHO, BRUJ, KARV, SAUD and HEID as well as the IGS stations ALGO, ALRT, ONSA, TROM, MADR and WES2 (REYK and HOFN are also IGS stations). Previous Kárahnjúkar GPS campaigns took place in August 2005, August 2006, August 2007 and August 2008. By conducting the measurements at the same time each year (August), the effect of seasonal variations should be minimised. Summaries of the 2005, 2006, 2007 and 2008 GPS campaigns are presented in *Ófeigsson et al.* (2005, 2006); *Ófeigsson* (2008); *Ófeigsson et al.* (2009). Each GPS station was occupied for one whole session (24 hours) and for a part of two session (8-16 hours), giving a set of three coordinate values for each campaign.

3 2009 GPS campaign

The 2009 GPS campaign was conducted in August 2009 by the Institute of Earth Sciences and a group from Landsvirkjun. It was conducted in the same manner as previous campaigns (35 benchamrks). The calculated coordinates from the 2009 campaign are presented in Table 1 Two groups on two jeeps participated in the campaign, one from Landsvirkjun and one from the Institute of Earth Sciences. A total number of 25 instruments were used: 2 pairs of Trimble 7400MSI receivers and (Compact L1/L2) TRM22020.00 antennas, one pair of Trimble NETR5 and (Zephyr Geodetic 2) TRM55971.00 antenna, 7 pairs of Trimble 5700 receivers and (Zephyr Geodetic) TRM41249.00 antennas, 10 pairs of Trimble 5700 receivers and (Zephyr Geodetic 1/2) TRM41249.00/TRM55971.00 antennas and 5 pairs of Trimble NETRS receivers and (Zephyr Geodetic) TRM41249.00 antennas. The campaign was conducted in the period from July 29, - August 19, 2009.

Table 1: Estimated coordinates (in ITRF2005 reference system) in 2009.

Point	x [m]	σ_x [m]	y [m]	σ_y [m]	z [m]	σ_z [m]
ALFD	2599642.4404	0.0025	-747114.4229	0.0027	5757626.0457	0.0040
DSTI	2608084.2848	0.0038	-736217.2332	0.0022	5755184.5629	0.0075
FADA	2603338.1462	0.0036	-747675.8121	0.0022	5755930.9943	0.0083
GRUN	2582199.6081	0.0036	-718008.7514	0.0022	5769023.1875	0.0079
HALS	2610918.2568	0.0029	-738682.6058	0.0018	5753663.3078	0.0058
HATU	2632703.4351	0.0025	-741354.4755	0.0017	5743624.7530	0.0053
HDAL	2605996.2561	0.0036	-725815.5980	0.0021	5757521.7215	0.0073
HLON	2612253.8469	0.0021	-743131.5113	0.0015	5752603.8230	0.0039
HRAU	2616052.2174	0.0019	-750700.9763	0.0015	5749819.6534	0.0038
HSTO	2607617.7412	0.0032	-744050.7410	0.0021	5754459.7992	0.0069
KRIN	2614404.6542	0.0021	-747730.3635	0.0015	5750927.9201	0.0044
KVAR	2613373.5227	0.0027	-752828.3311	0.0018	5750748.4613	0.0055
KVEA	2611373.6845	0.0025	-759806.2240	0.0017	5750688.2084	0.0052
LAFE	2618922.1281	0.0034	-721853.3721	0.0021	5752169.4407	0.0074
LAVE	2600325.4730	0.0033	-735996.6365	0.0021	5758748.2740	0.0069
MISA	2609037.2803	0.0029	-743263.9498	0.0019	5753856.4894	0.0062
MISV	2609019.9318	0.0034	-743275.8697	0.0021	5753857.7096	0.0074
MISS	2609055.8563	0.0025	-743308.0191	0.0017	5753840.8918	0.0054
NYSA	2620384.7836	0.0033	-737611.2632	0.0020	5749647.6951	0.0074
SADA	2606224.7153	0.0025	-741695.5551	0.0016	5755350.8457	0.0050
SFEL	2608044.6869	0.0021	-737942.5993	0.0015	5755038.9134	0.0044
SHAL	2608894.0228	0.0020	-741836.0635	0.0015	5754126.0688	0.0040
SNES	2622806.9863	0.0034	-725652.7182	0.0021	5749893.2969	0.0066
SNSK	2621860.1070	0.0027	-734112.6345	0.0018	5749433.2093	0.0058
THMY	2612283.1544	0.0026	-746861.3746	0.0017	5752054.8014	0.0055
THUD	2614654.0806	0.0029	-730655.9638	0.0020	5753084.3476	0.0059
TROL	2611527.1507	0.0021	-745466.2567	0.0015	5752556.9698	0.0042
TUNG	2611307.7180	0.0028	-731586.2050	0.0020	5754376.8908	0.0057
VEOR	2615478.4193	0.0023	-740777.9980	0.0016	5751319.7051	0.0047
VEVO	2609155.0153	0.0019	-748772.8425	0.0015	5753233.3411	0.0038
VIKD	2592243.6902	0.0026	-740904.0973	0.0027	5761679.2179	0.0044

4 Results

The results for the Kárahnjúkar GPS-campaigns are shown in Figures 1-16. As noted by *Ófeigsson* (2008), the crustal deformation observed in relation to the initial filling of Hálslón(Figures 3 and 12) was somewhat smaller then expected. The horizontal results are precented in a reference frame of stable Eurasian plate (zero velocity means then that the station is moving in the same manner as the stable interior of the Eurasian plate) and the vertical results are in the ITRF2005 reference frame as presented by *Altamimi et al.* (2007) (see Appendix). The main result, during the inintal filling, showed an average subsidence of (14 ± 10) mm and horizontal displacements close to the dams showed an extension across Hálslón (39 ± 6) mm in direction (329 ± 7) , for the same period (*Ófeigsson*, 2008). In the period between February 2007 and April 2008 intensive swarm of deep seated earthquakes 14-22 km were recorded under Upptyppingar and Álftadalsdyngja approximately 25 km away from Hálslón (*Jakobsdóttir et al.*, 2008). InSAR (Interferometric synthetic aperture radar) interferograms spanning the interval show a broad inflation extending to Kárahnjúkar area. This inflation signal and the earthquake swarm have been interpreted to bee due to intrusion of magma into the lower crust beneath Álftadalsdyngja (*Hooper et al.*, 2008). During the summer of 2007, the reservoir filling correlated in time with the first intrusion episodes at Álftadalsdyngja (at that time located beneath Upptyppingar). Some of the crustal deformation observed during the 2006-2007 period can therefore be a result of the intrusion, especially west of Hálslón. This requires some reevaluation of the conclusions made about the horizontal displacements observed west of Hálslón during the initial filling in 2006-2007. It seems apparent now that the east displacements observed during this period are due to inflation of a magma body intruding into the lower crust beneath Upptyppingar.

The most notable observations in 2007-2008 (Figures 5 and 13) is the large scale inflation centered beneath the Álfdadalsdyngja shield volcano. The effect of the inflation is observed on stations located as far as Snæfell. The vertical component of this broad inflation, geometrically coincides quite well with previously observed InSAR interferograms presented by *Hooper et al.* (2008). The horizontal velocities suggest however that the area influenced by of the inflation is even greater then the vertical GPS component and the InSAR observations suggest. It is apparent that the intrusion at Álftadalsdyngja masks the potential crustal response of the refilling of Hálslón in 2007-2008. In order to evaluate a possible crustal response due to the reservoir refilling, the signal associated with the intrusion needs to be removed. On the ohter hand, the widespread inflation influences the crustal movements at Kárahnjúkar. Even though the effect is small, the gradient of the signal compresses the crust under Hálslón counteracting the filling process.

The results of the latest GPS campaign (Figures 7 and 15), and velocities between 2008-2009, indicate that the inflation observed at Álftadalsdyngja between 2007-2008 is no longer influencing crustal movements in Kárahnjúkar. Comparing the results from 2005-2006 and 2008-2009 reveal no significant difference, indicating negligible crustal response to the reservoir refilling. The residuals between the first (2005-2006) and the last (2008-2009) observation interval (Figure 17) reveal small but irregular movements around Hálslón.

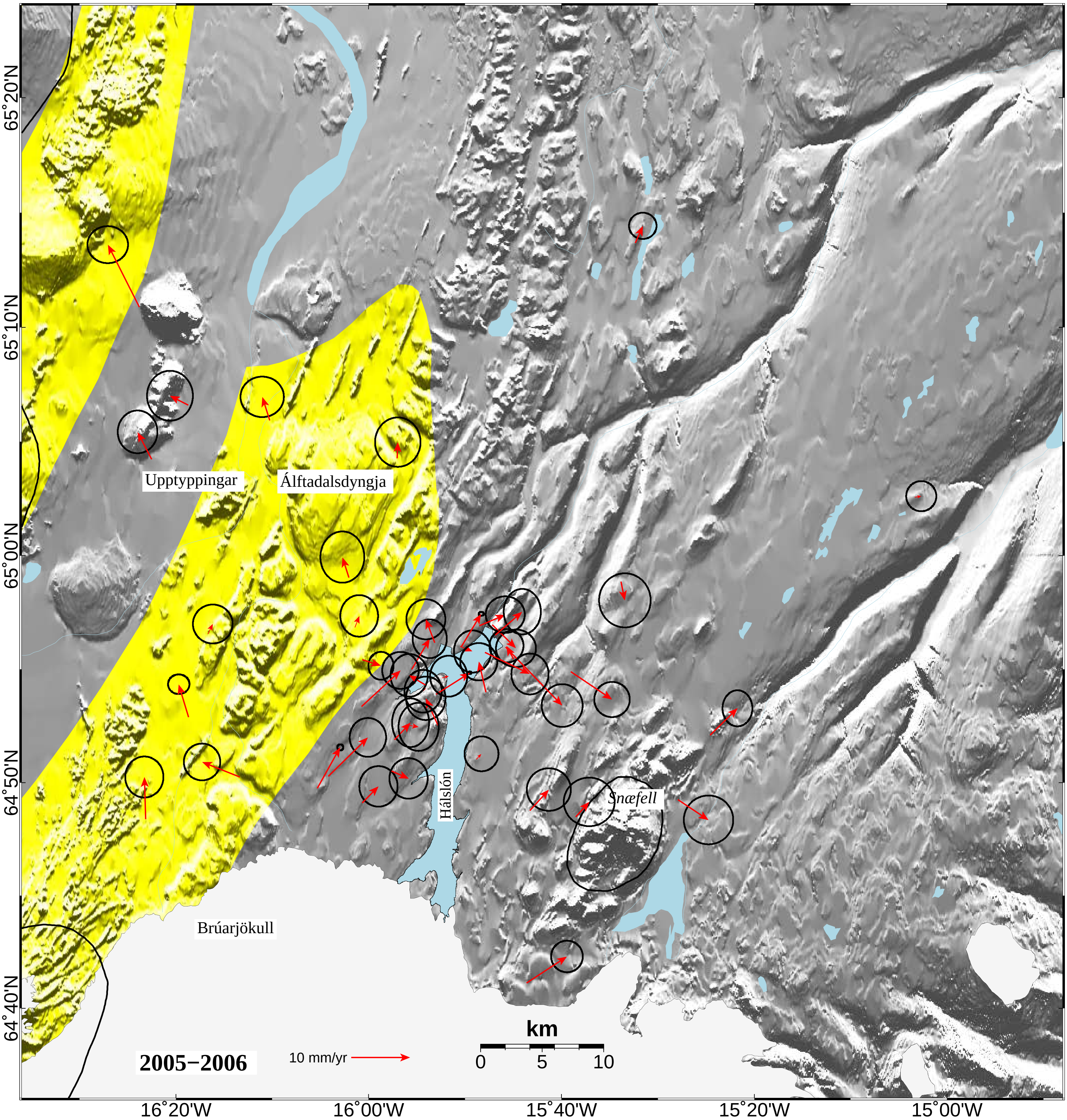

Figure 1: Horizontal velocities derived from the 2005 and 2006 GPS-campaigns, relative to stable Eurasian plate.

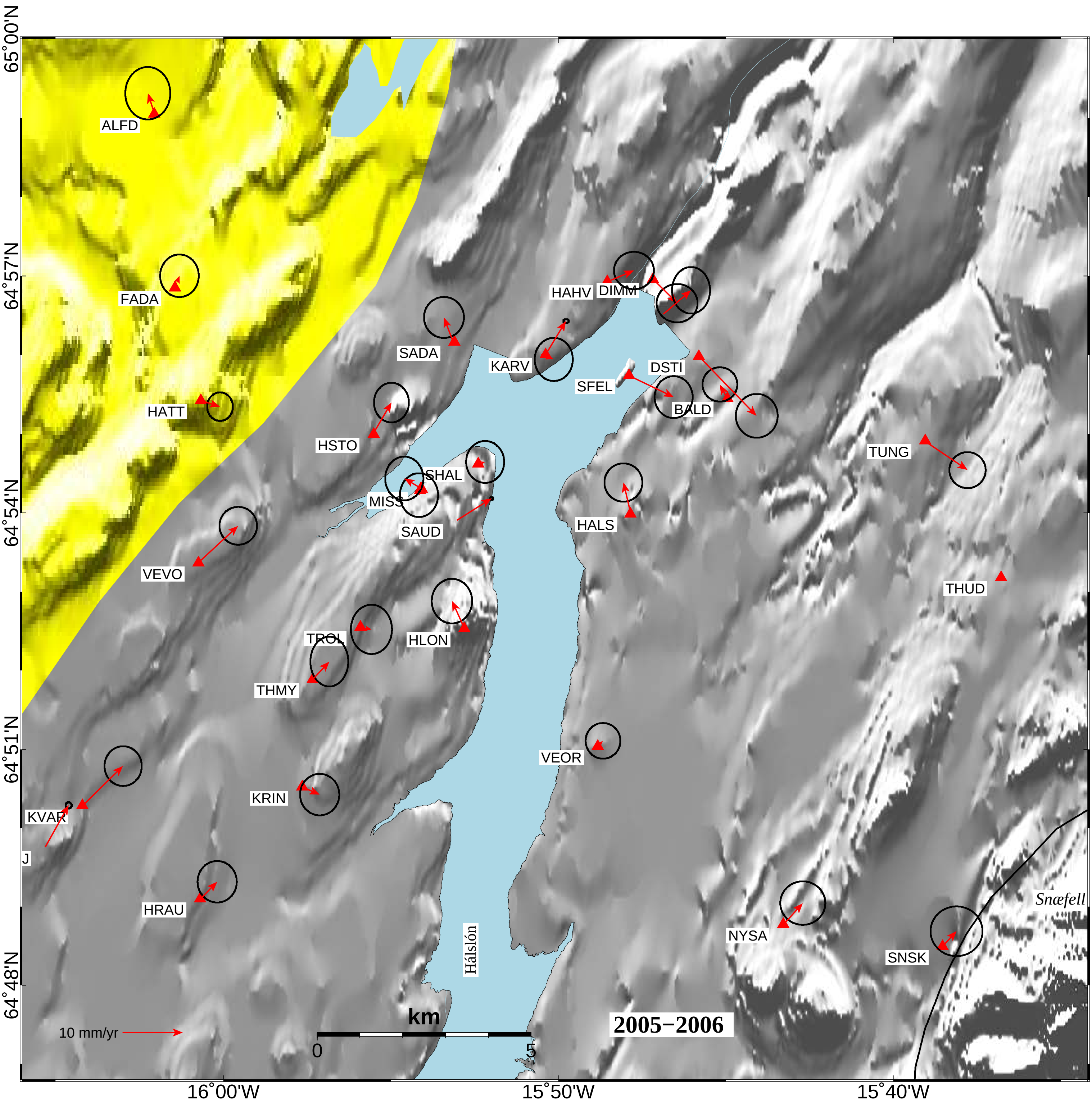

Figure 2: Horizontal velocities in the reservoir area derived from the 2005 and 2006 GPS-campaigns, relative to stable Eurasian plate.

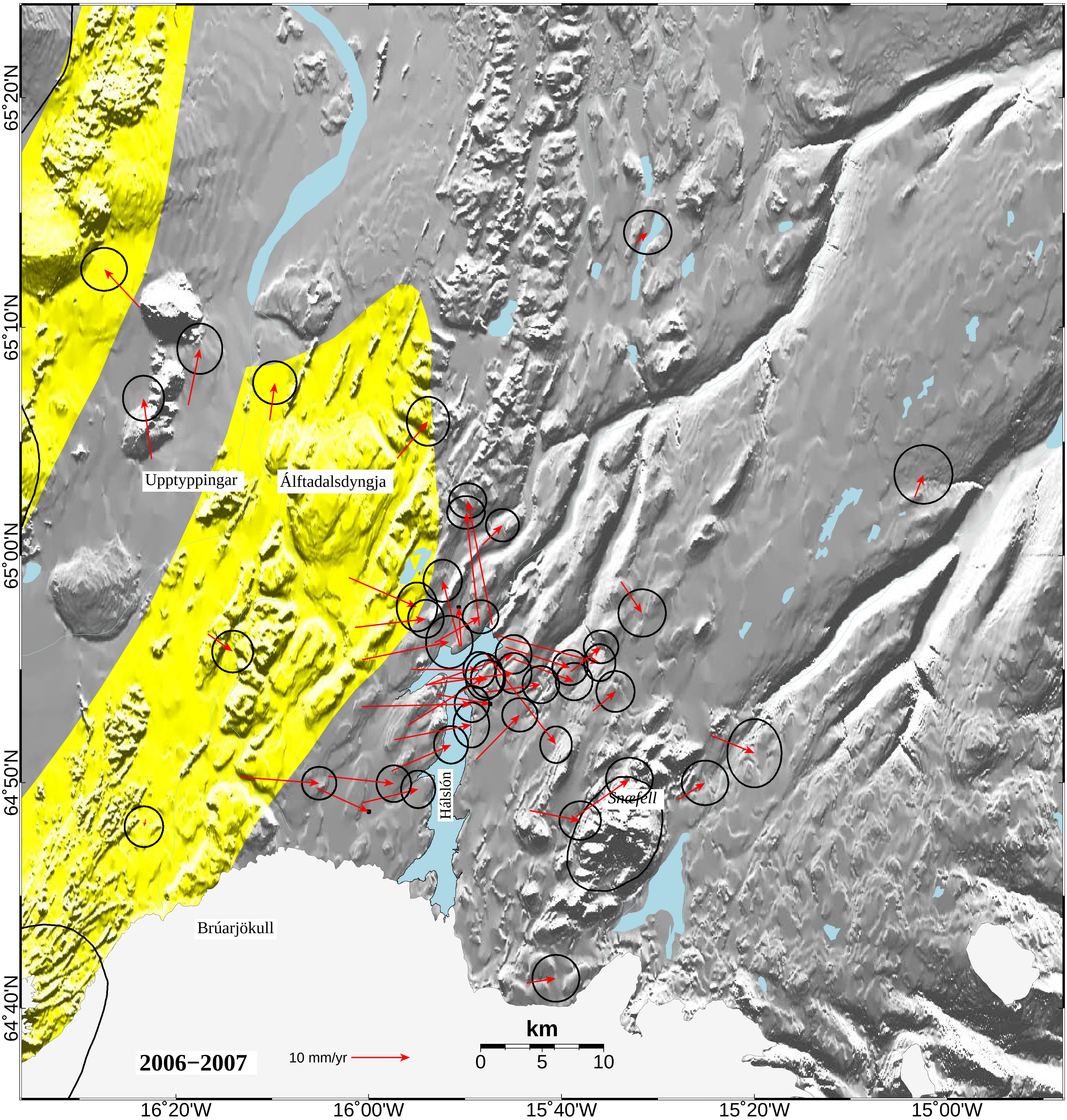

Figure 3: Horizontal velocities derived from the 2006 and 2007 GPS-campaigns, relative to stable Eurasian plate.

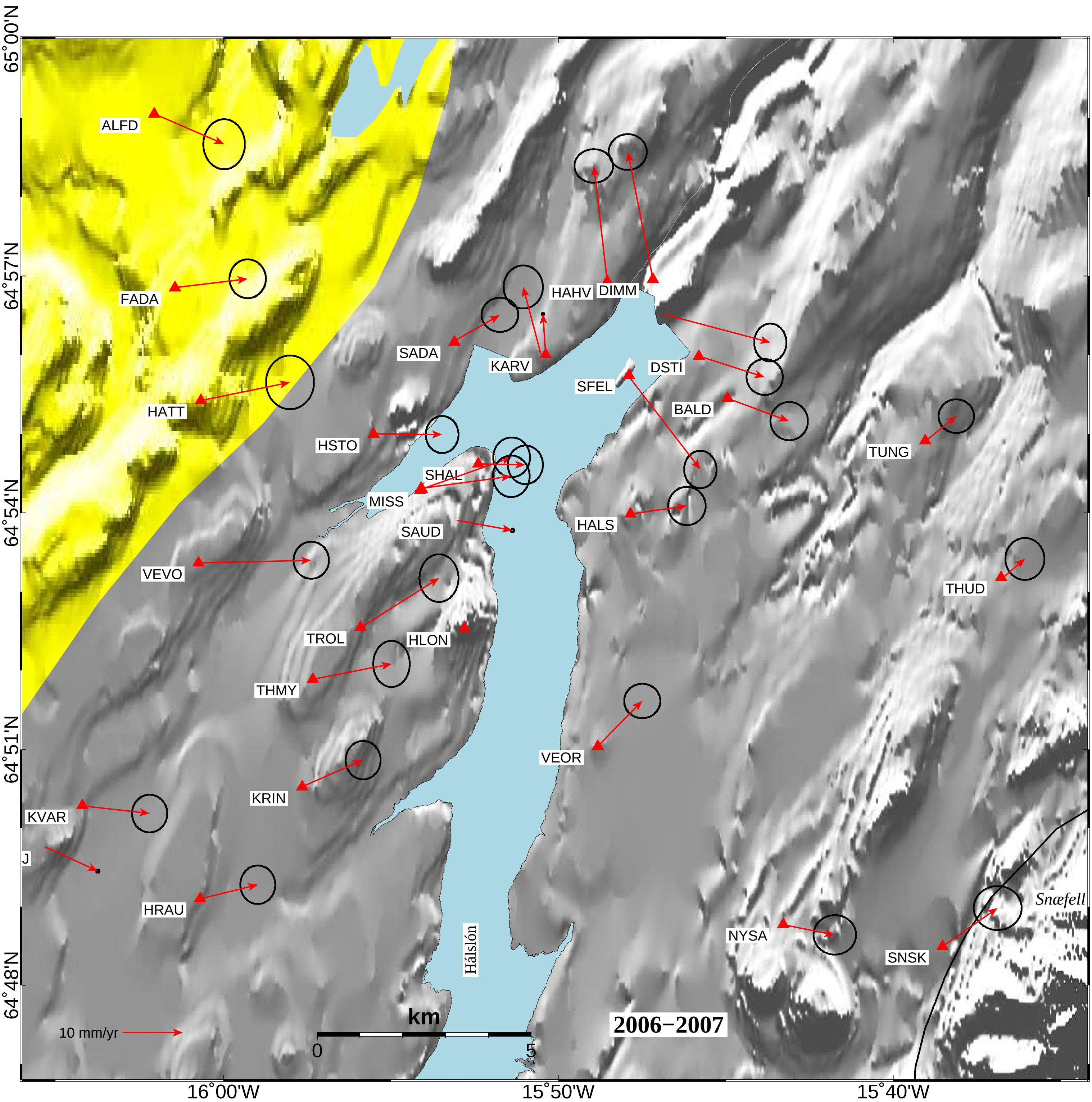

Figure 4: Horizontal velocities in the reservoir area derived from the 2006 and 2007 GPS-campaigns, relative to stable Eurasian plate.

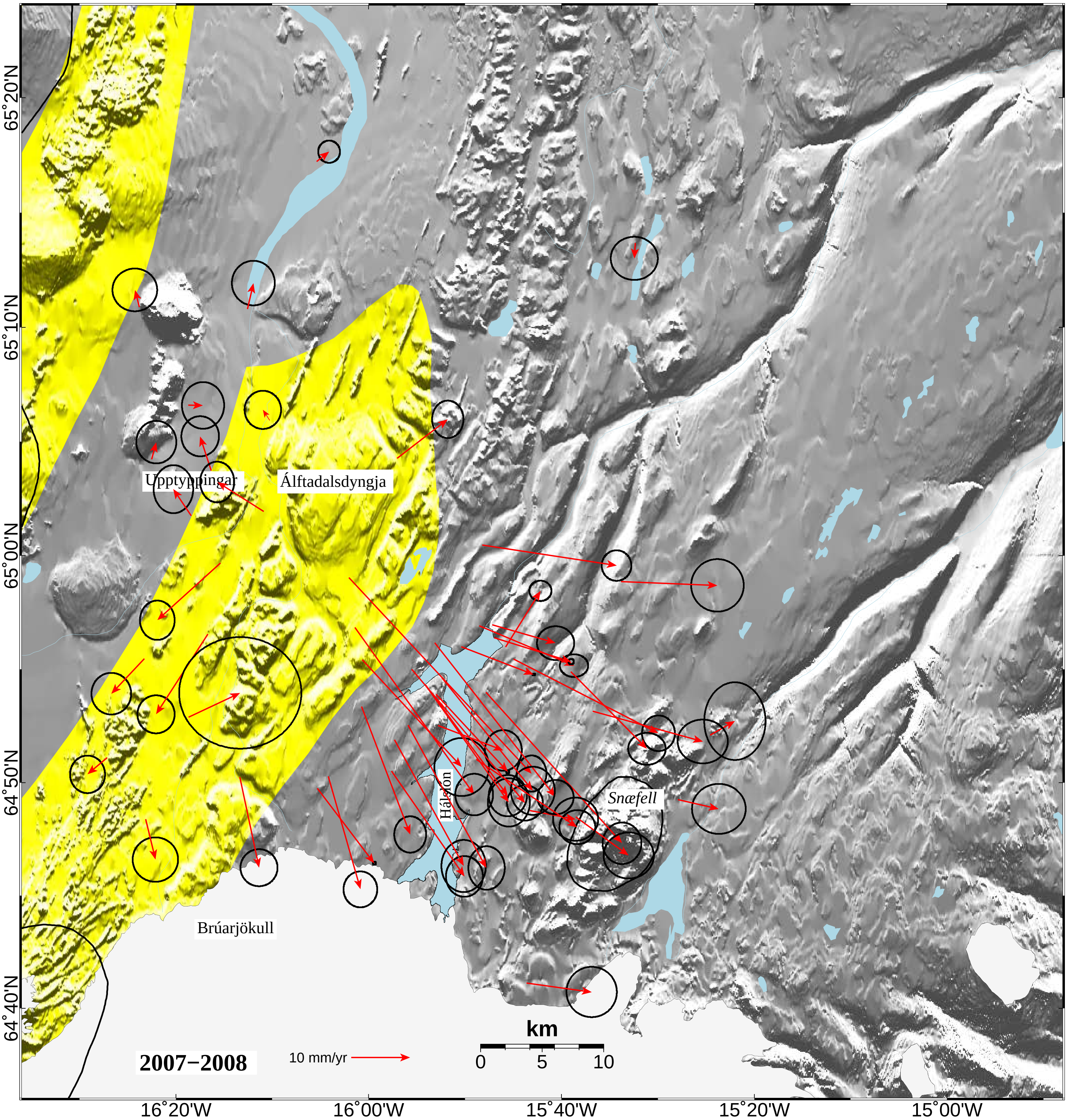

Figure 5: Horizontal velocities derived from the 2007 and 2008 GPS-campaigns, relative to stable Eurasian plate.

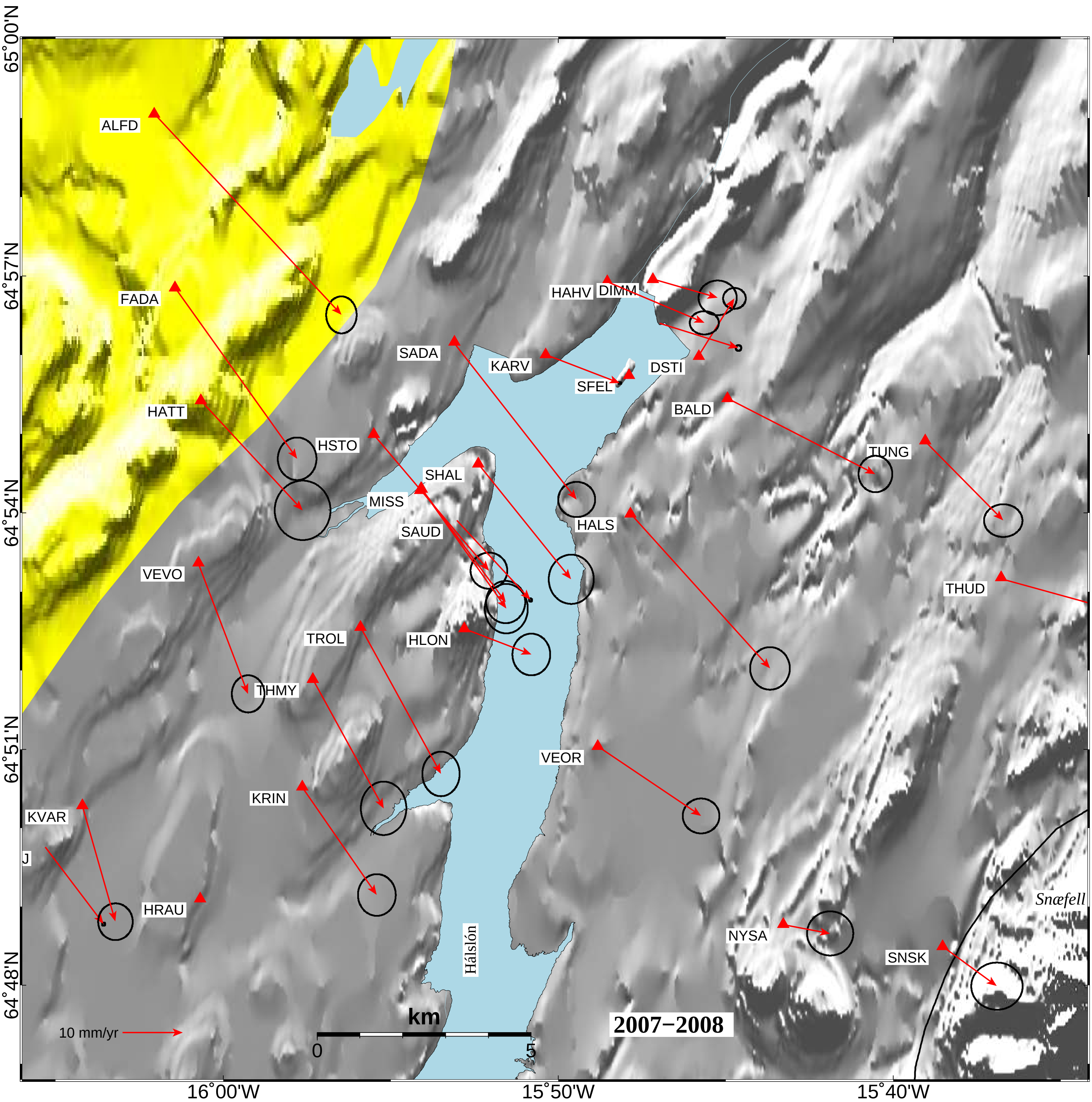

Figure 6: Horizontal velocities in the reservoir area derived from the 2007 and 2008 GPS-campaigns, relative to stable Eurasian plate.

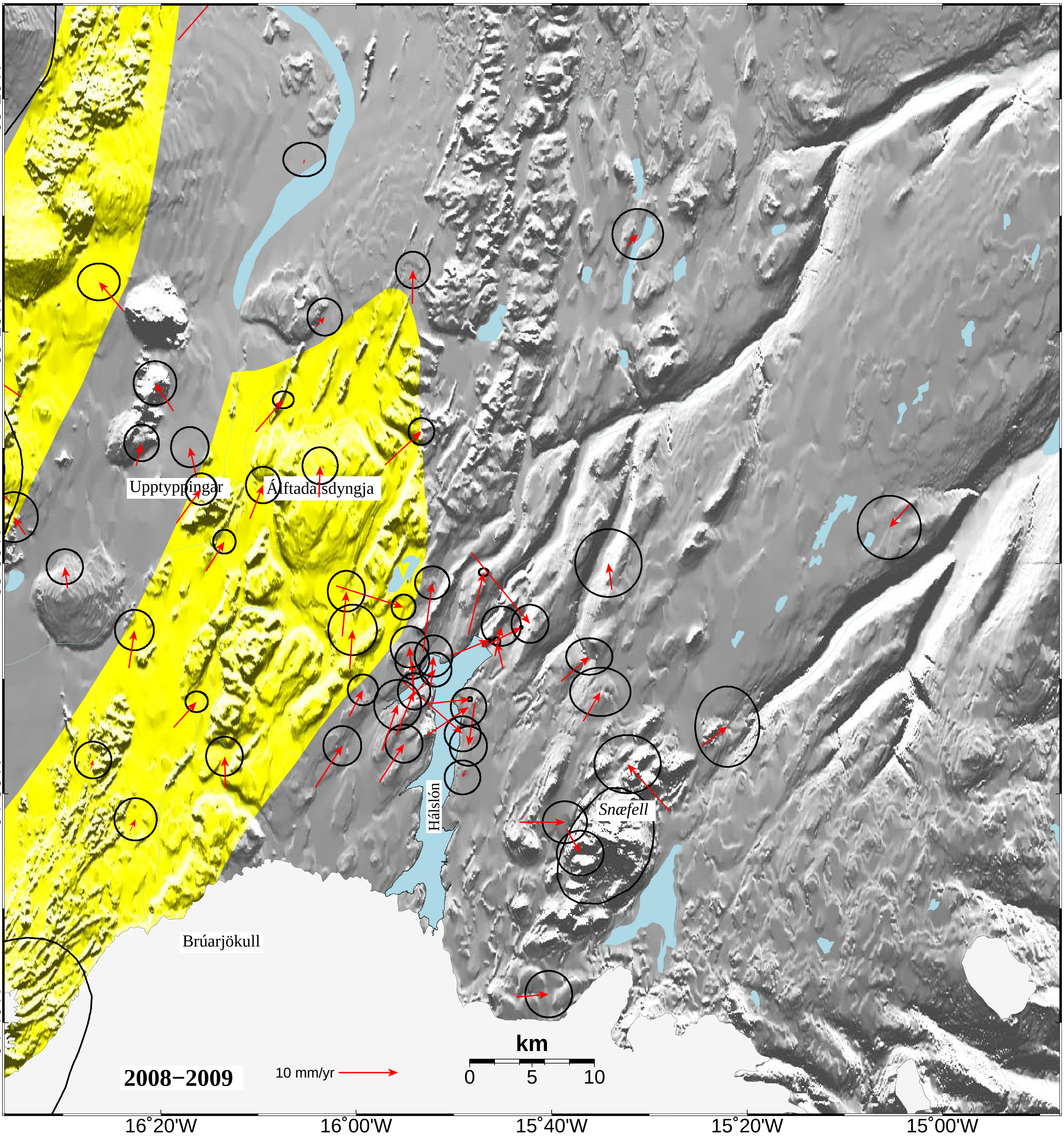

Figure 7: Horizontal velocities derived from the 2008 and 2009 GPS-campaigns, relative to stable Eurasian plate.

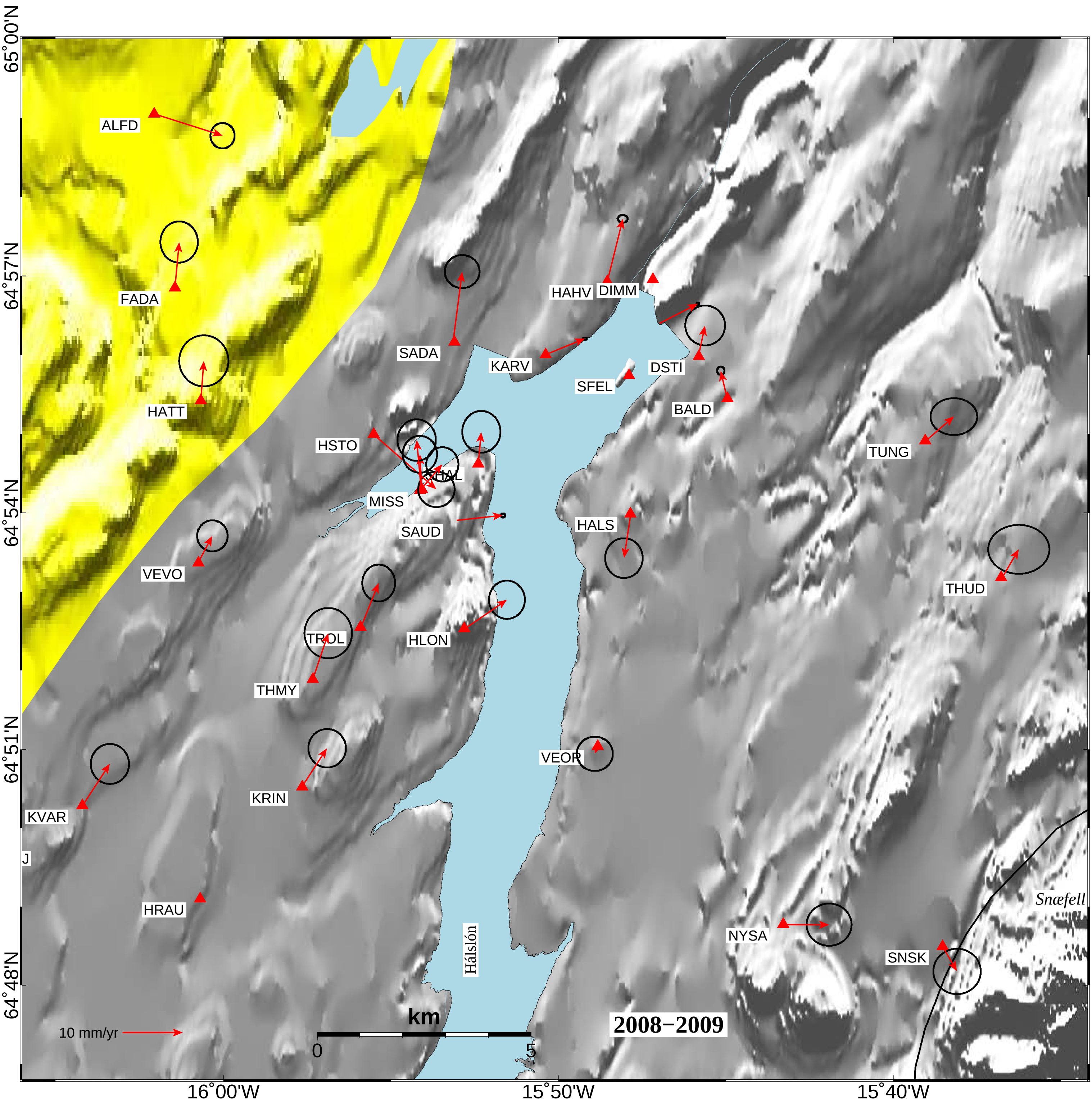

Figure 8: Horizontal velocities in the reservoir area derived from the 2008 and 2009 GPS-campaigns, relative to stable Eurasian plate.

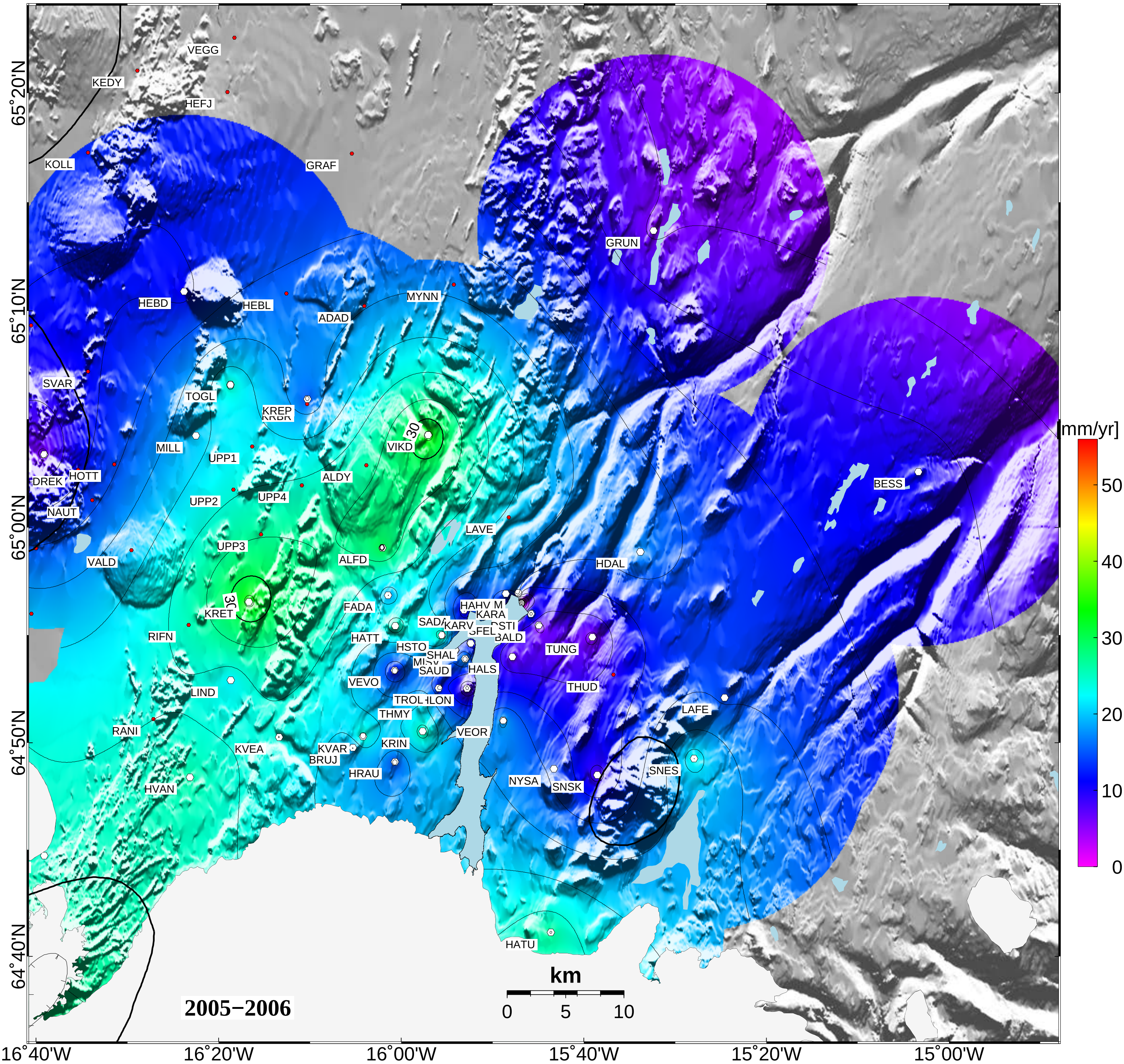

Figure 9: Vertical velocitiy field derived from the 2005 and 2006 GPS-campaigns. The white hexagons are stations that contribute to the velocity field.

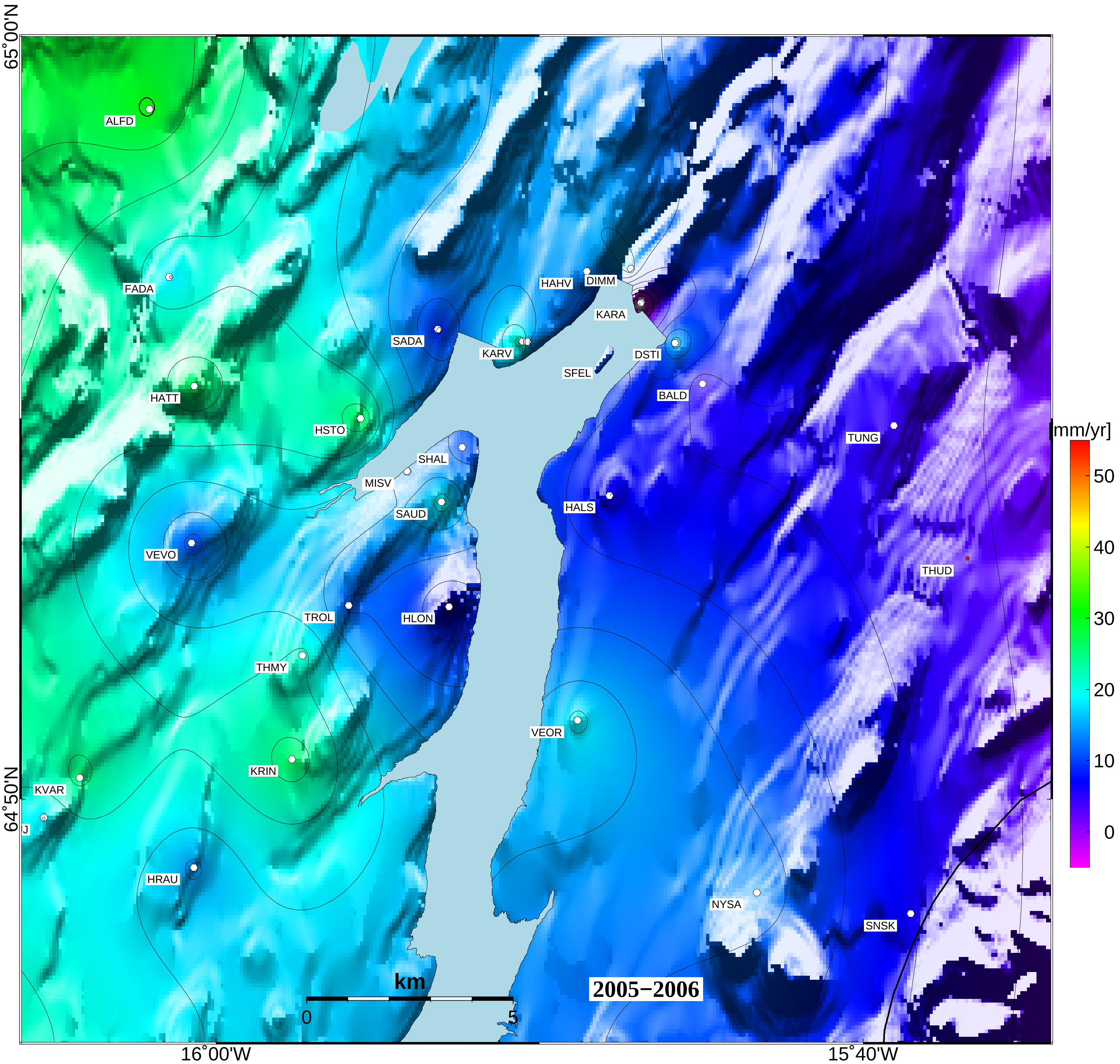

Figure 10: Vertical velocitiy field in the reservoir area derived from the 2005 and 2006 GPS-campaigns. The white hexagons are stations that contribute to the velocity field.

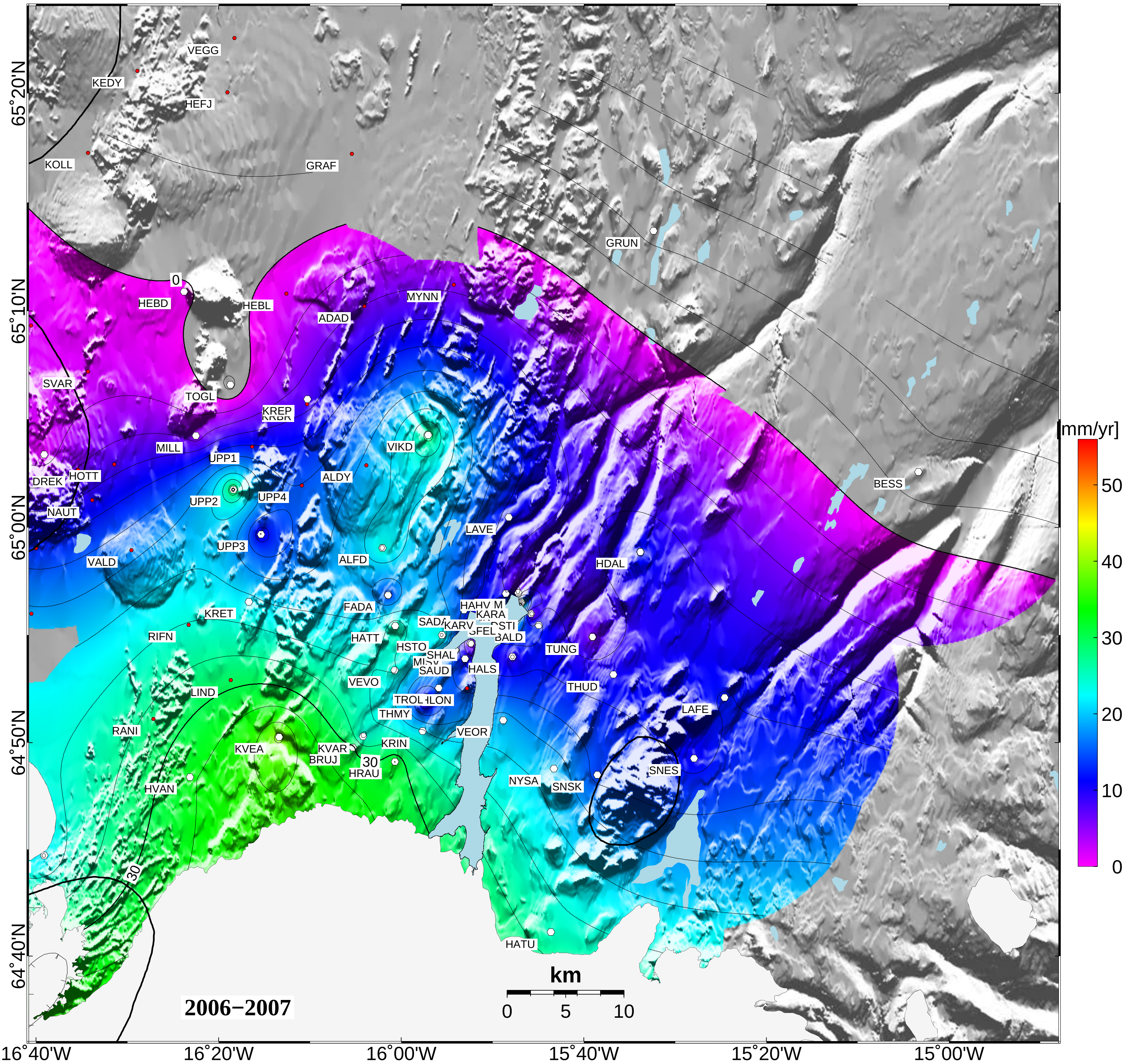

Figure 11: Vertical velocitiy field derived from the 2006 and 2007 GPS-campaigns. The white hexagons are stations that contribute to the velocity field.

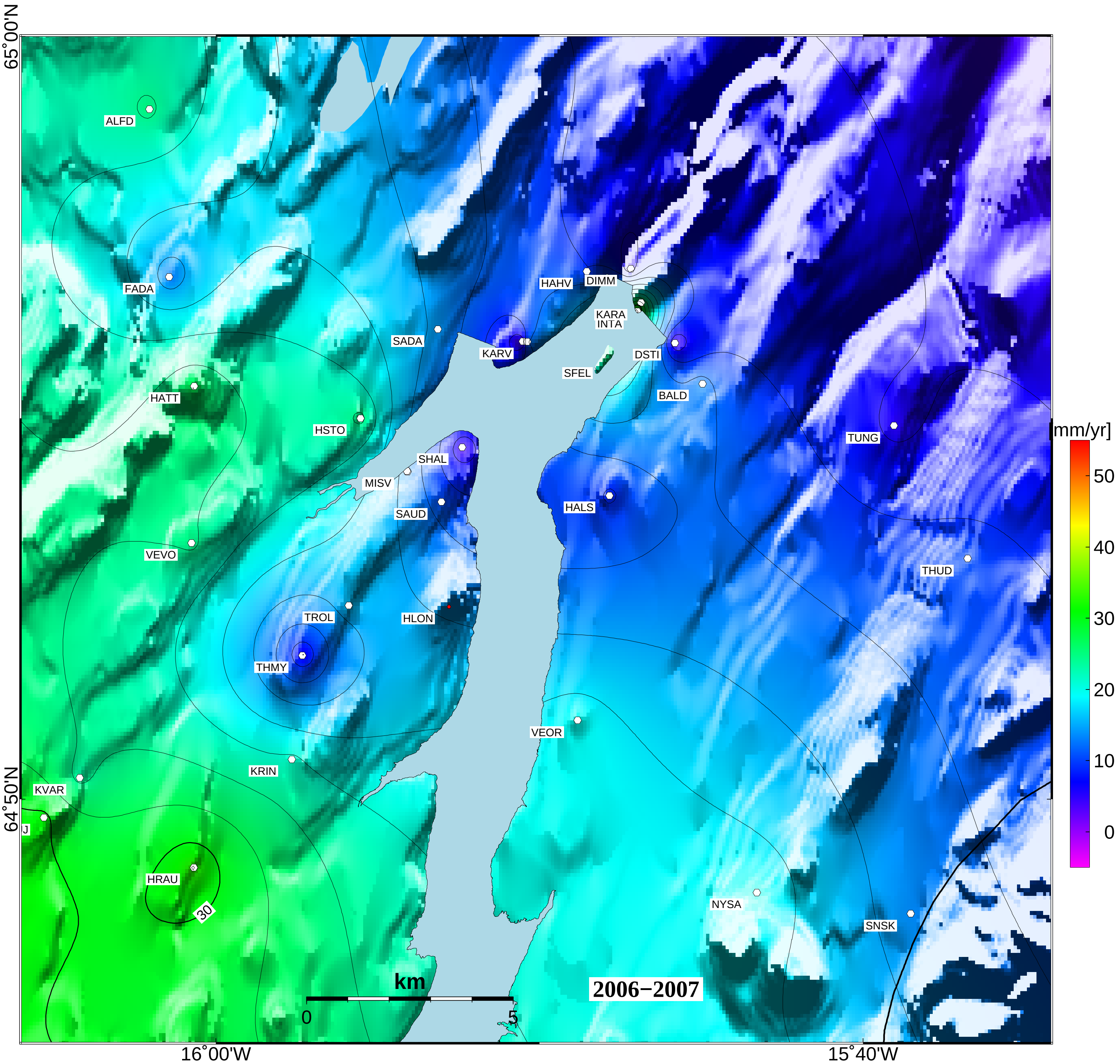

Figure 12: Vertical velocitiy field in the reservoir area derived from the 2006 and 2007 GPS-campaigns. The white hexagons are stations that contribute to the velocity field.

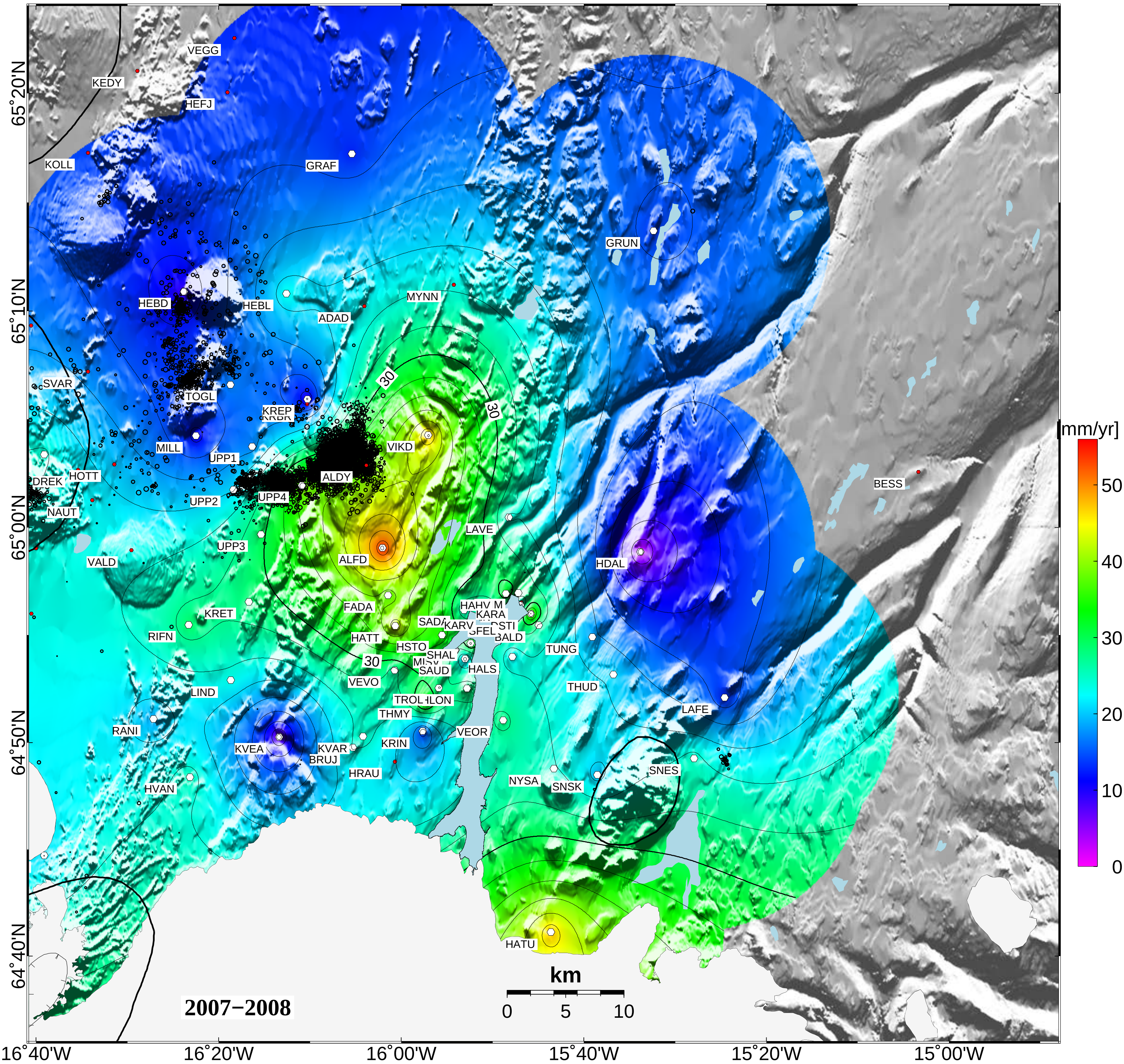

Figure 13: Vertical velocitiy field derived from the 2007 and 2008 GPS-campaigns. The white hexagons are stations that contribute to the velocity field.

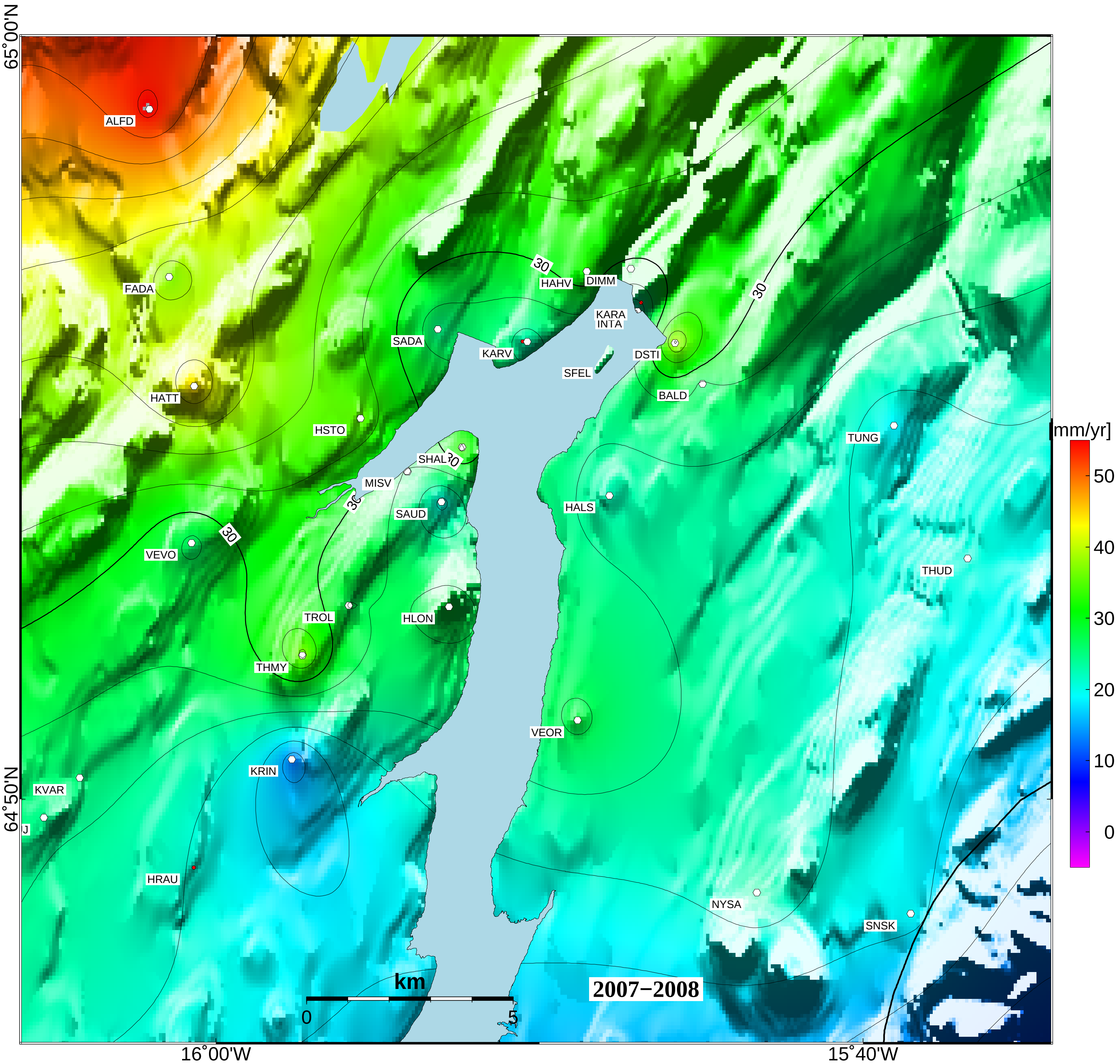

Figure 14: Vertical velocitiy field in the reservoir area derived from the 2007 and 2008 GPS-campaigns. The white hexagons are stations that contribute to the velocity field.

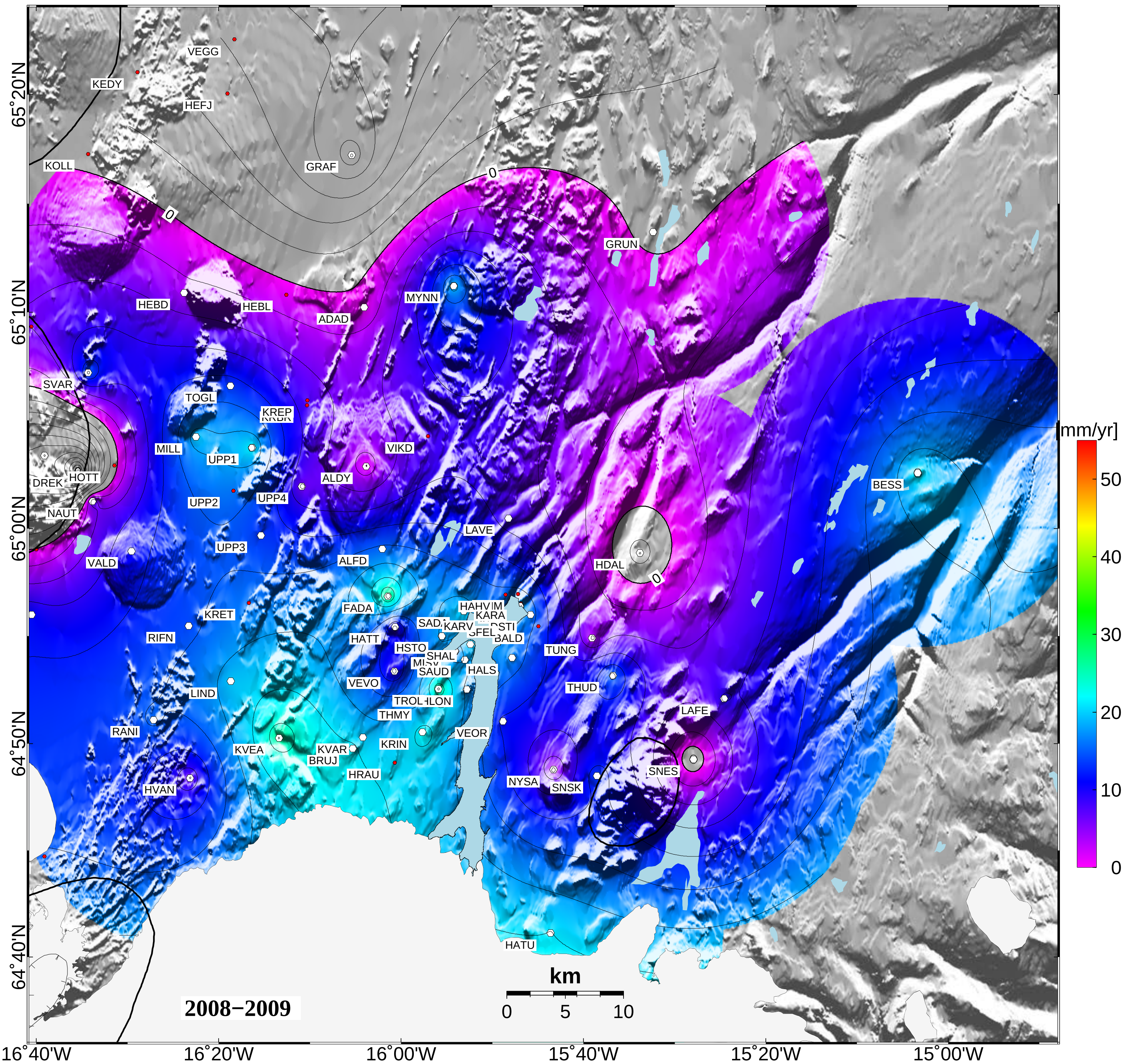

Figure 15: Vertical velocitiy field derived from the 2008 and 2009 GPS-campaigns. The white hexagons are stations that contribute to the velocity field.

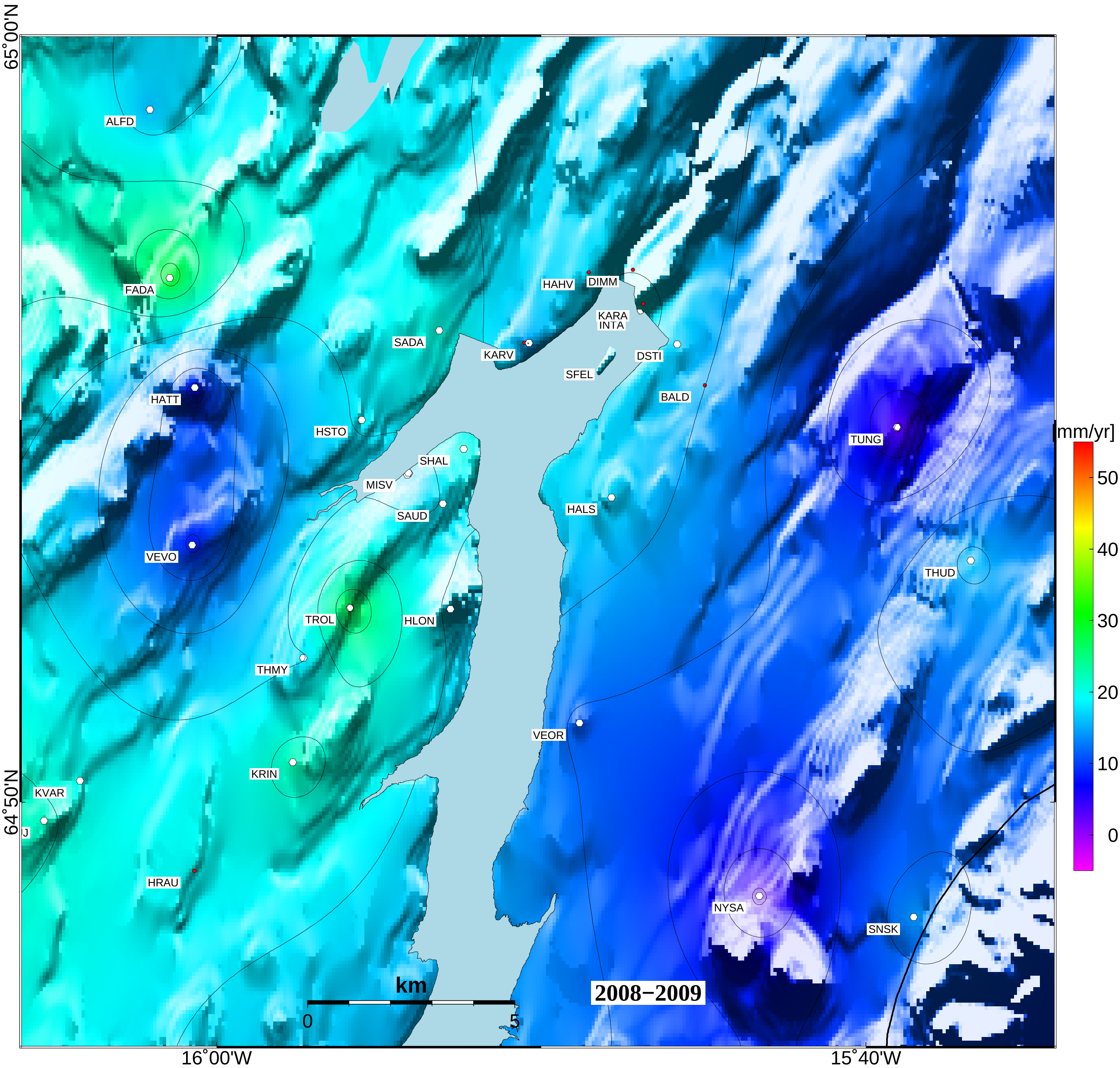

Figure 16: Vertical velocitiy field in the reservoir area derived from the 2008 and 2009 GPS-campaigns. The white hexagons are stations that contribute to the velocity field.

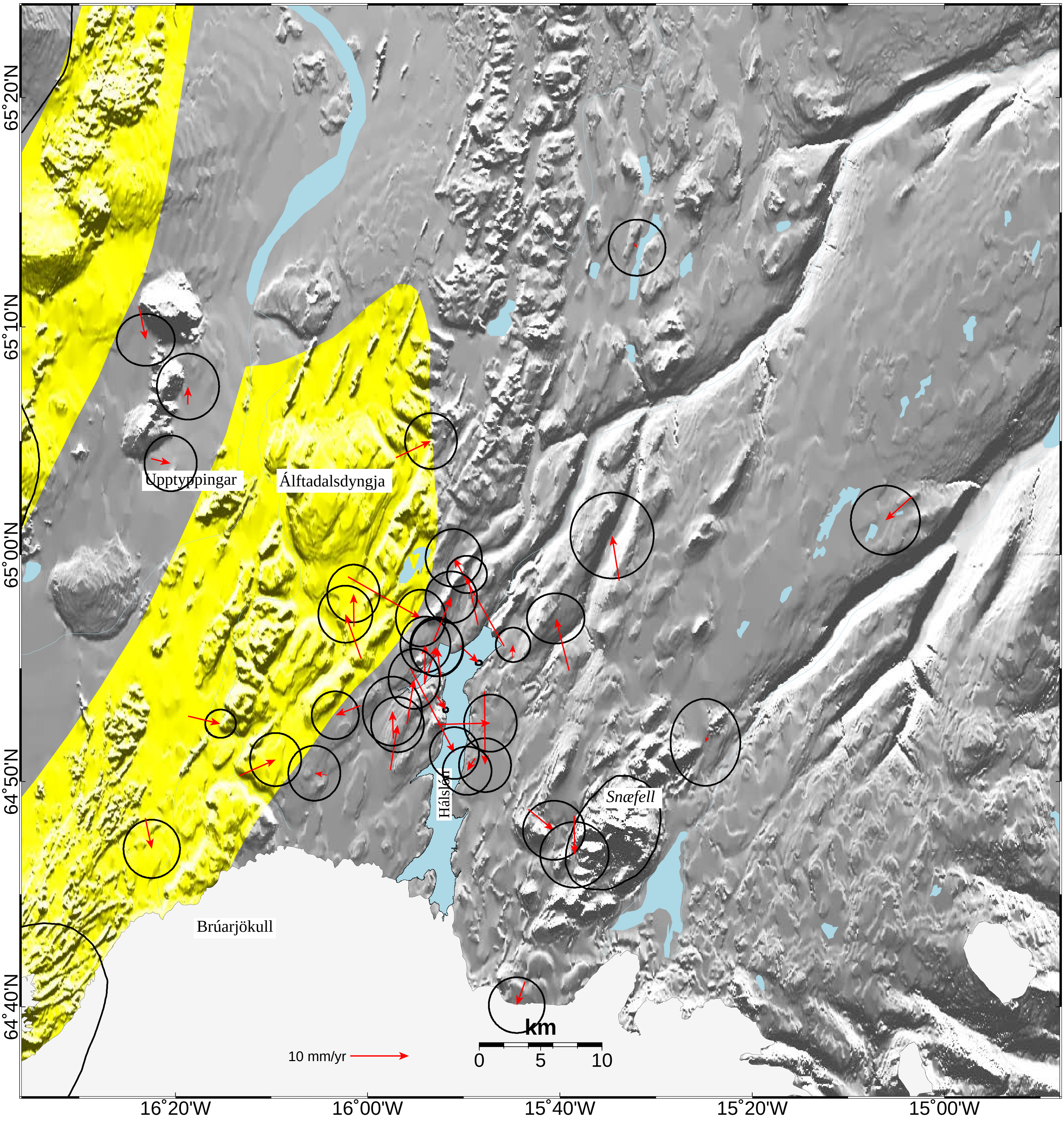

Figure 17: Residual velocities when velocities in 2005-2006 1 have been subtracted from velocities in 2008-2009 7.

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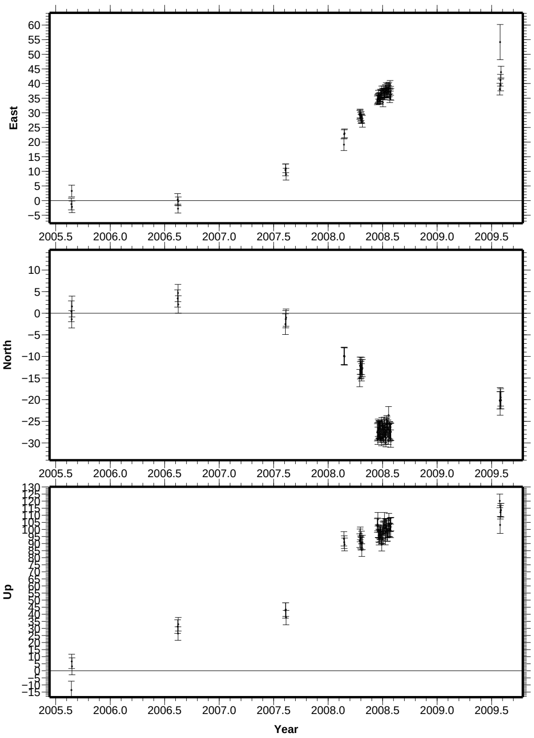
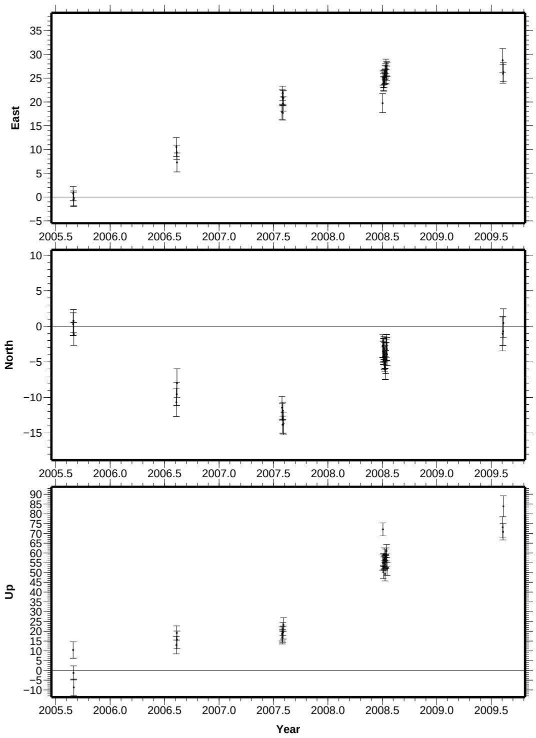
Appendix

The following figures show the time series of displacements from 2005-2009. The the plate velocity of the Eurasian plate (ITRF05 refference frame) has been subtracted from the time series. The rotation pole of Eurasia in ITRF05 refference frame is (56.330 deg,-95.979 deg,0.261 deg/my) as published by *Altamimi et al.* (2007).

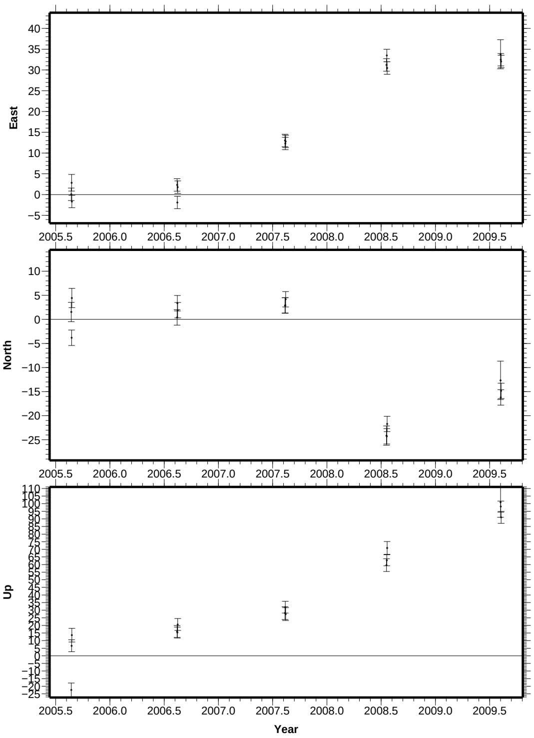
ALFD



DSTI



FADA



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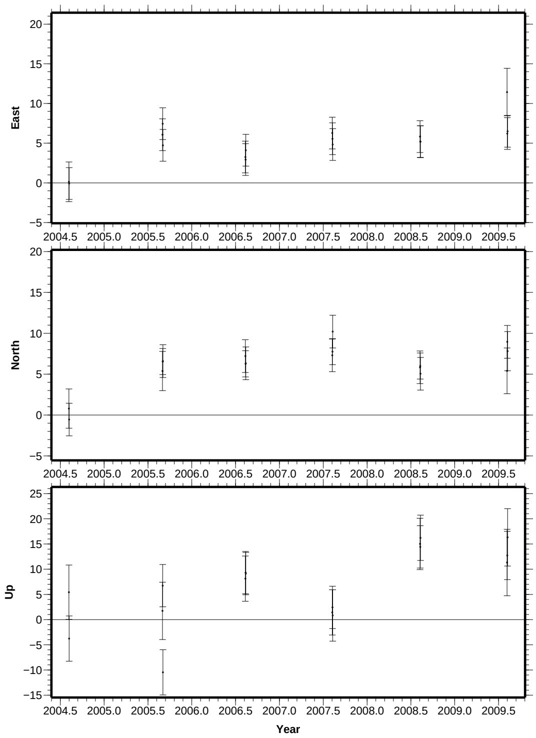

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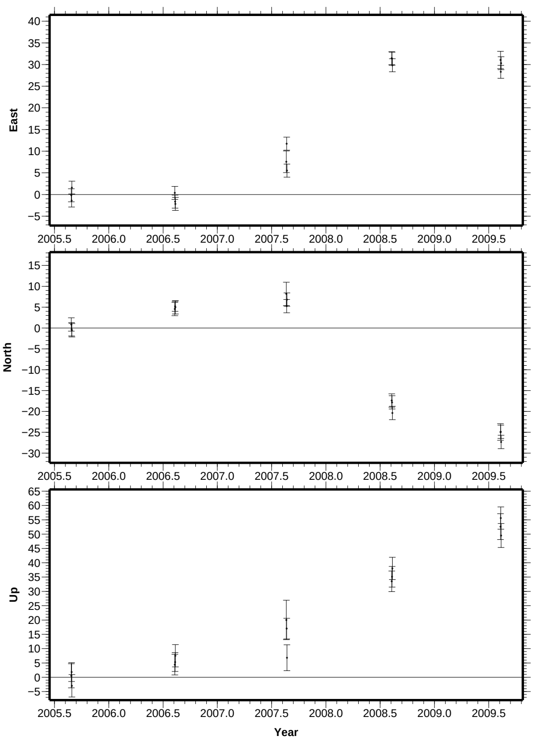

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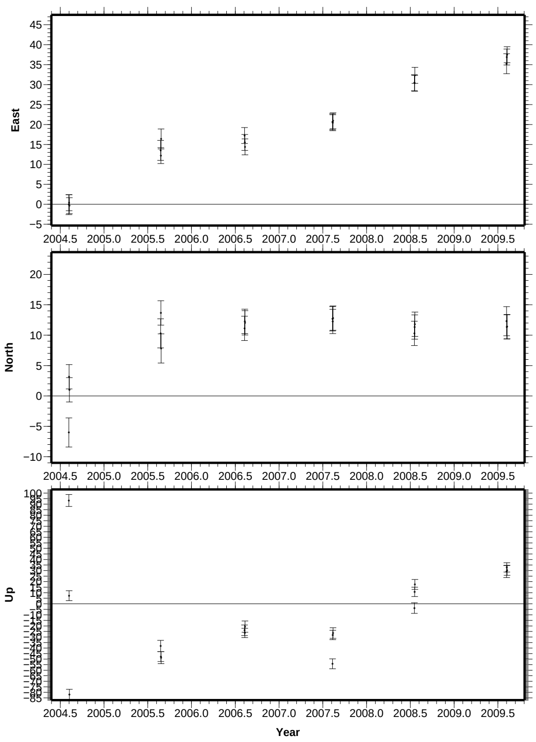

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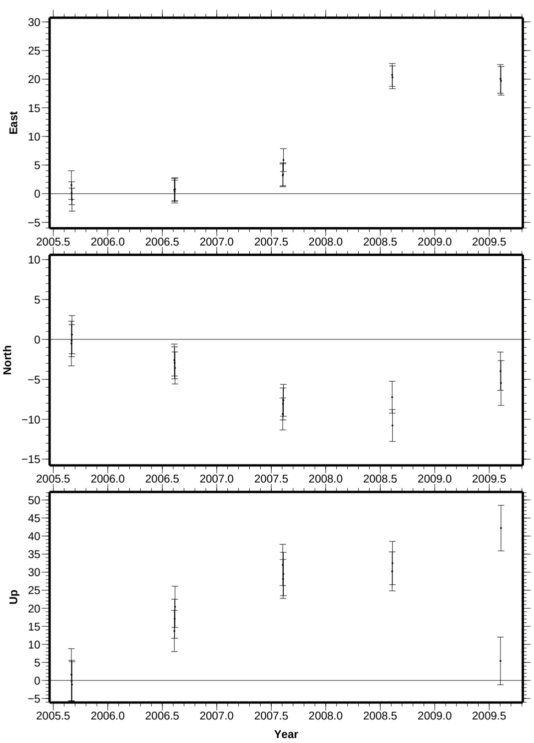
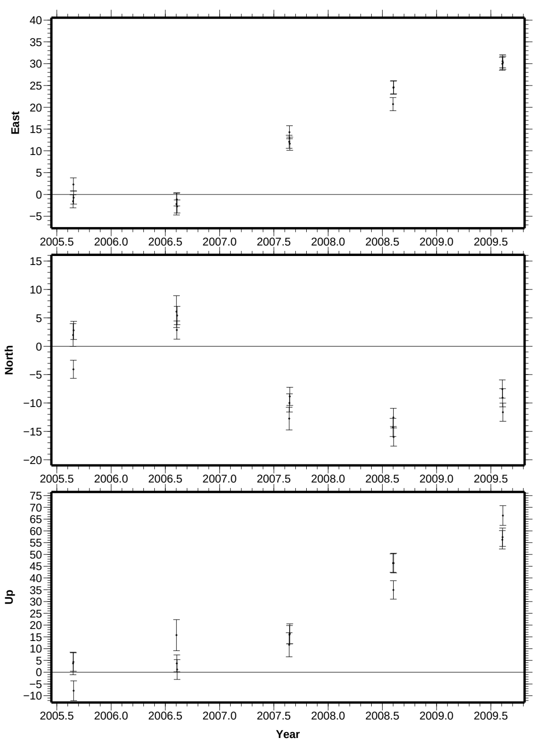
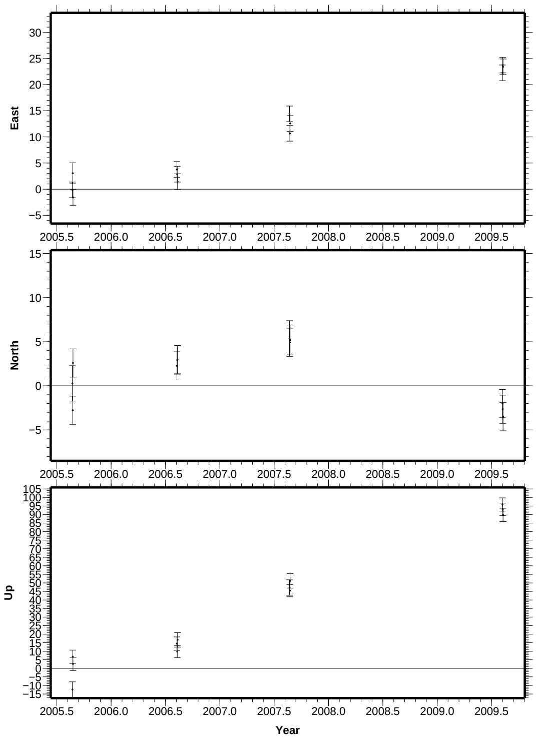


HLON



HRAU



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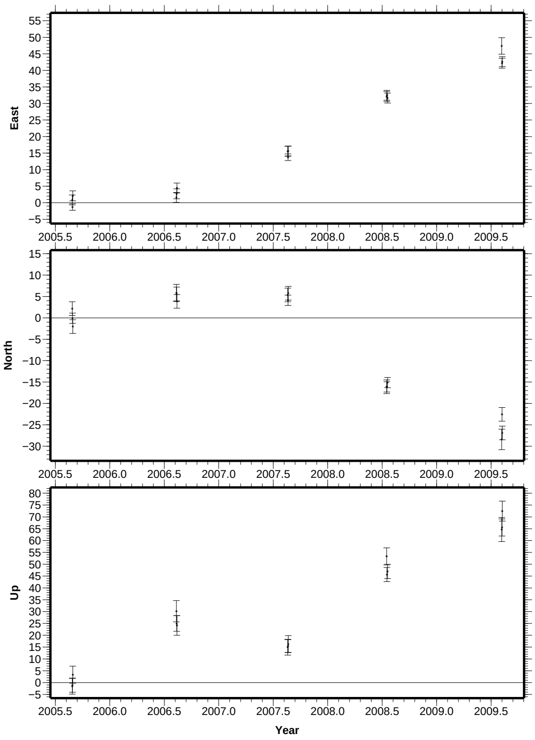
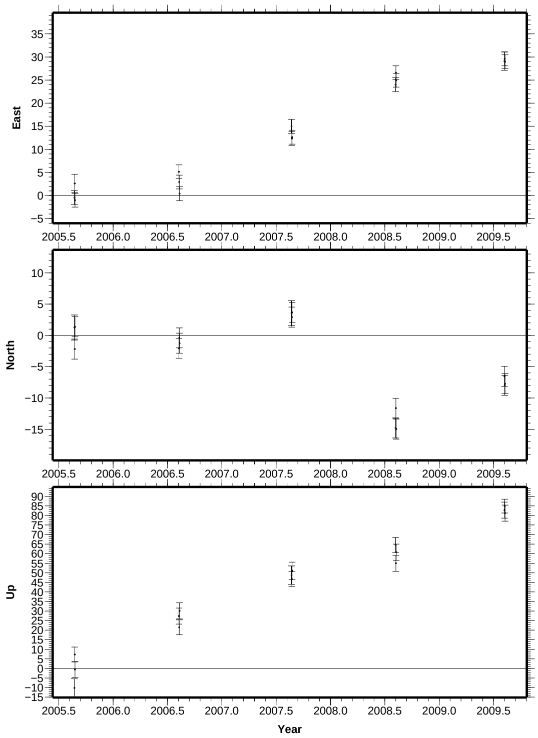


KRIN



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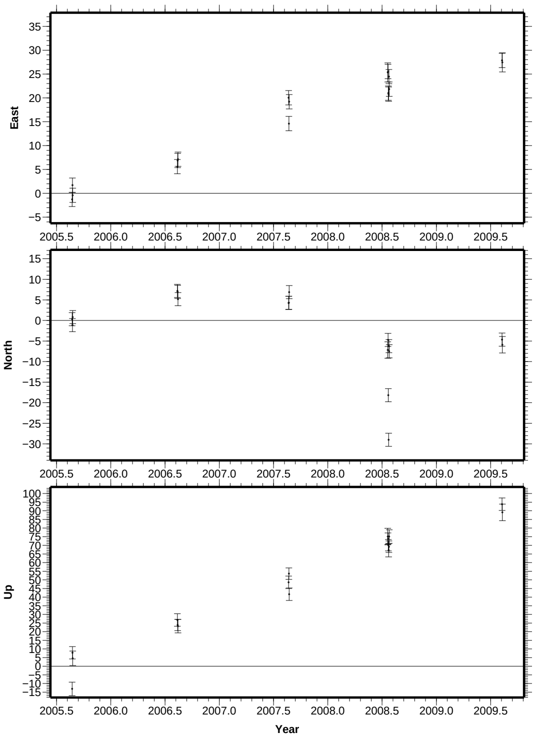
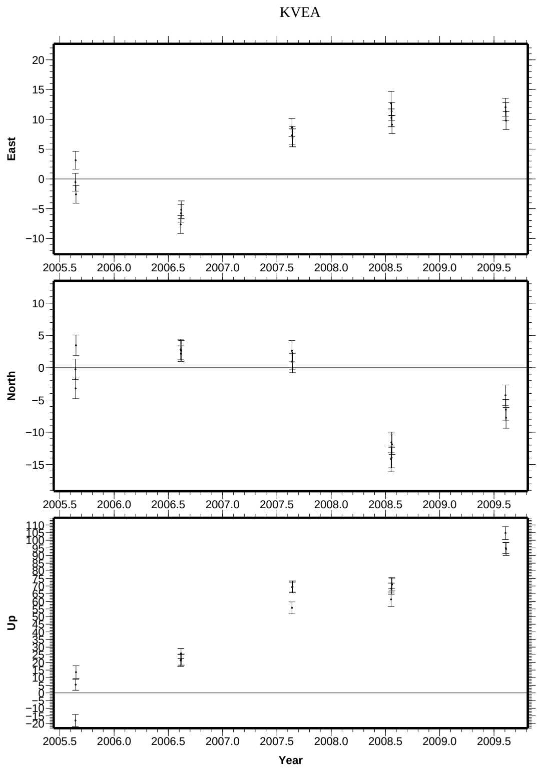
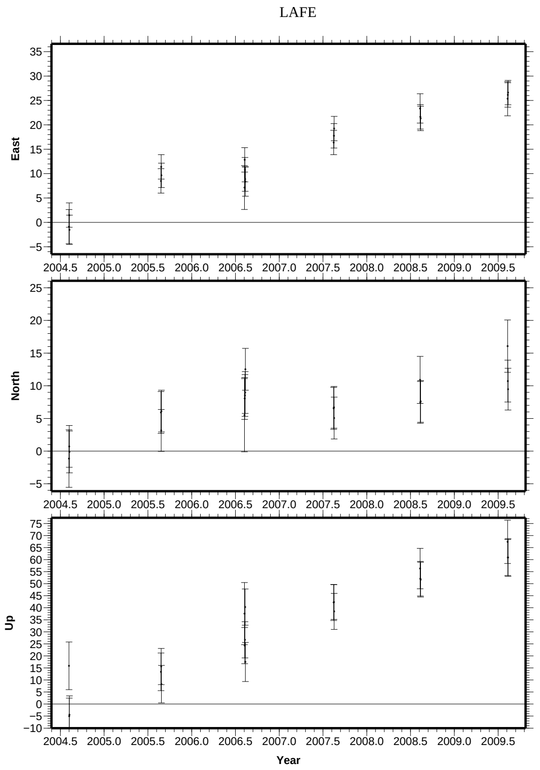
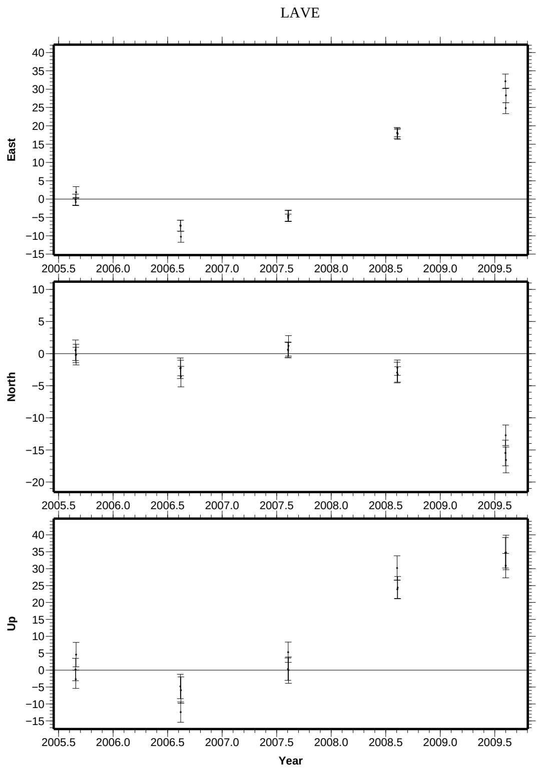
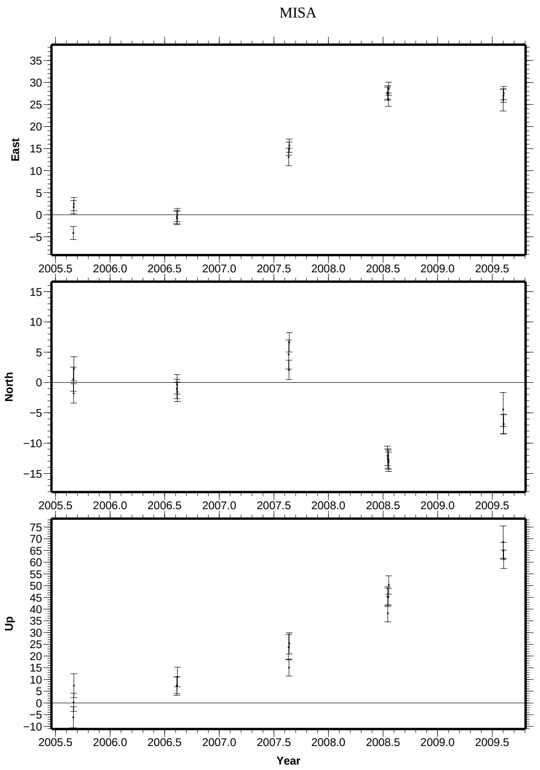


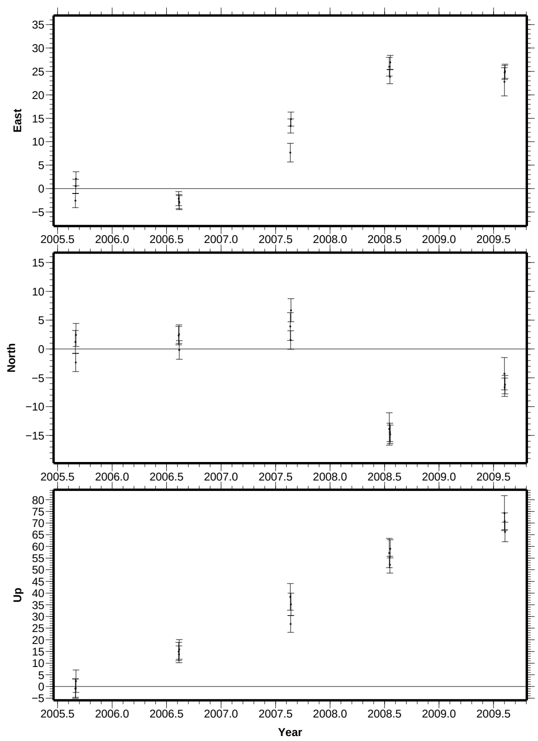

KVEA
East
North
Up
Year


LAFE
East
North
Up
Year


LAVE
East
North
Up
Year


MISA
East
North
Up
Year

MISV



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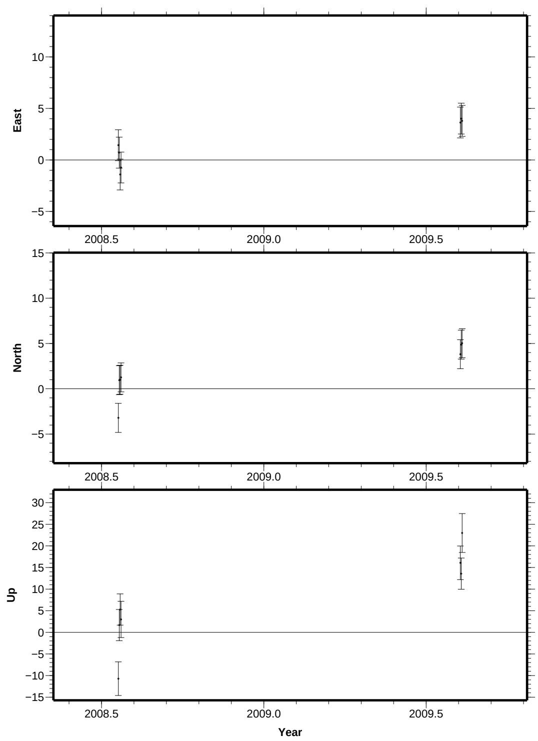

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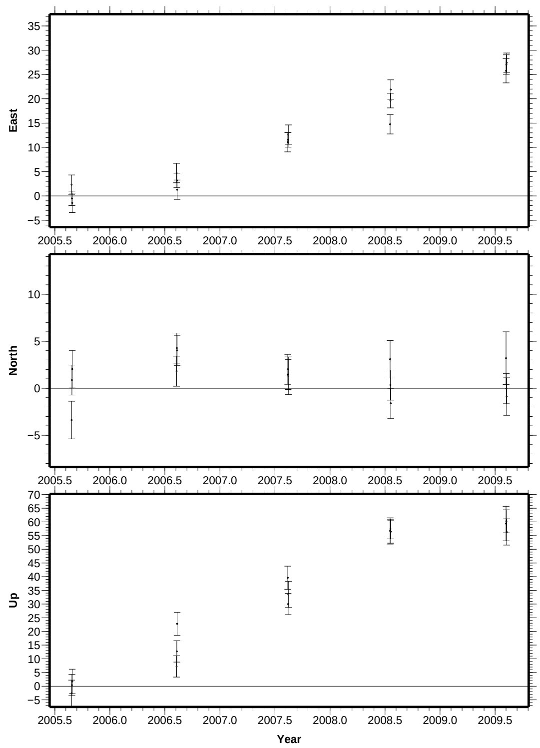

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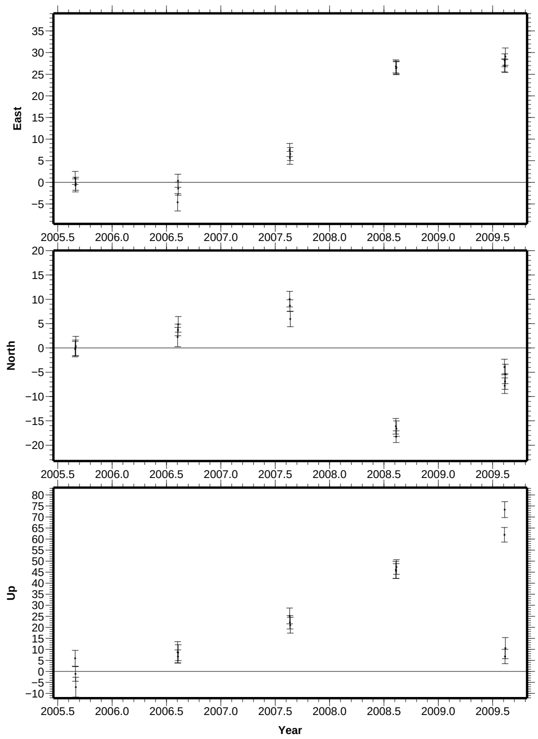

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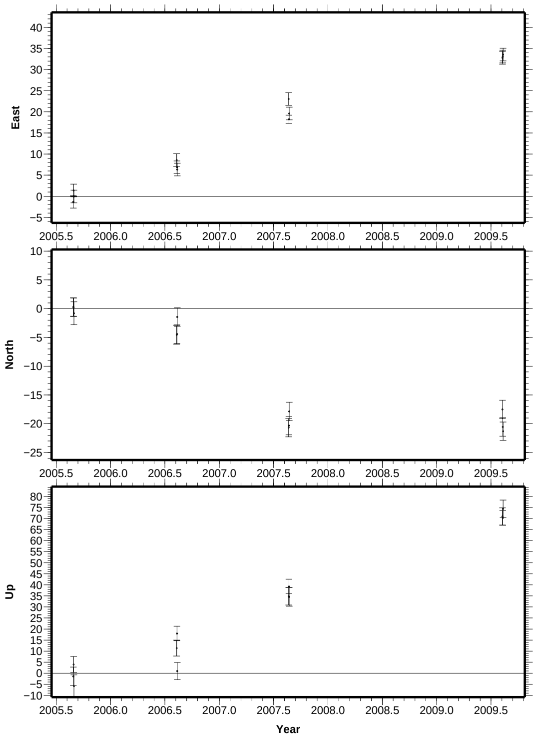

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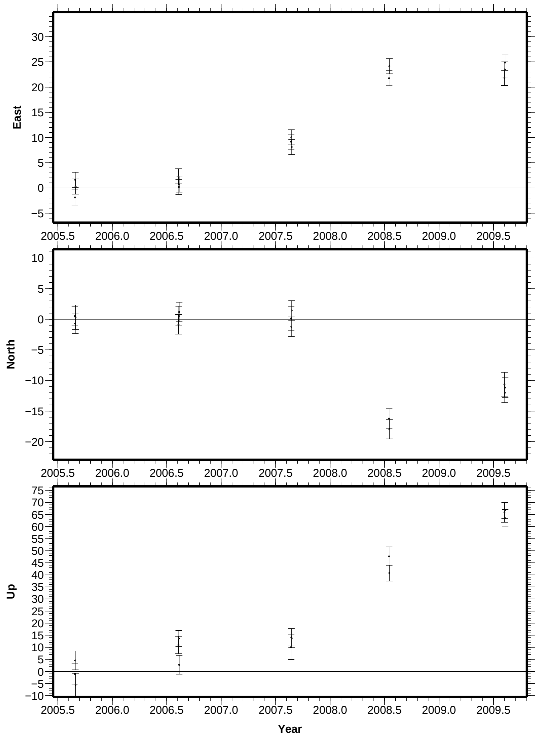

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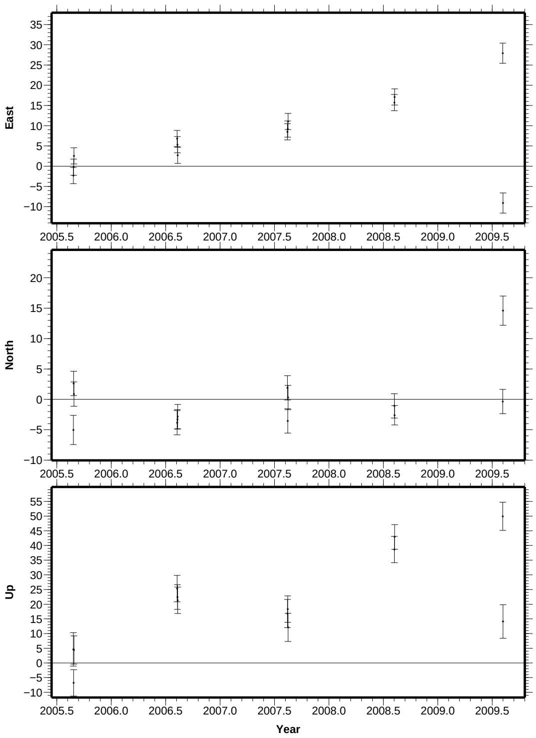

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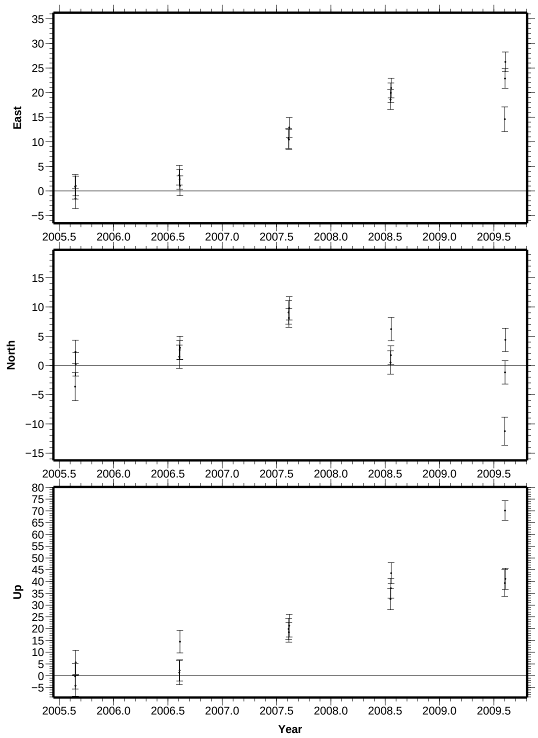

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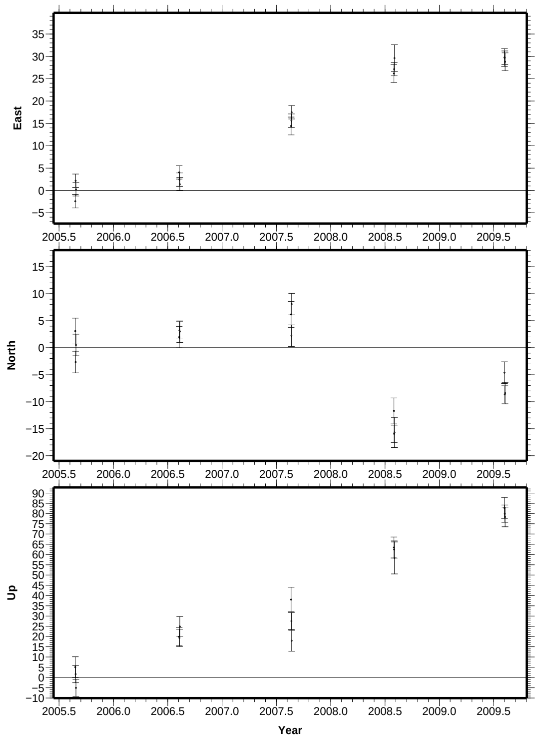

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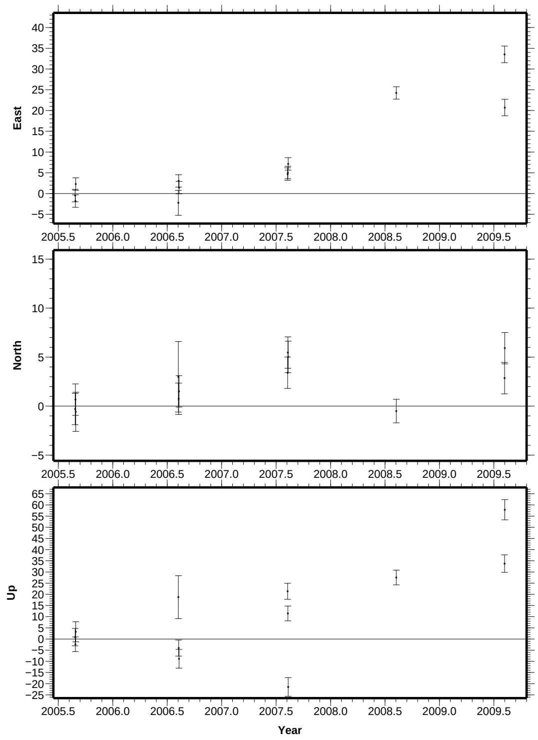

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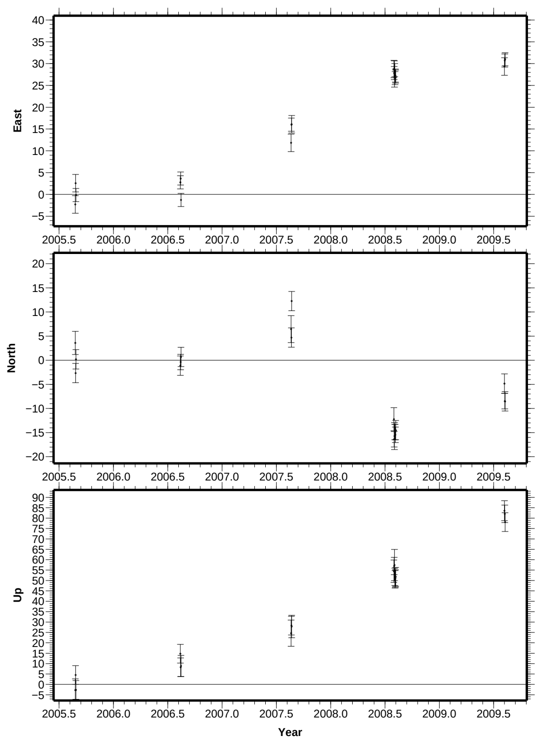
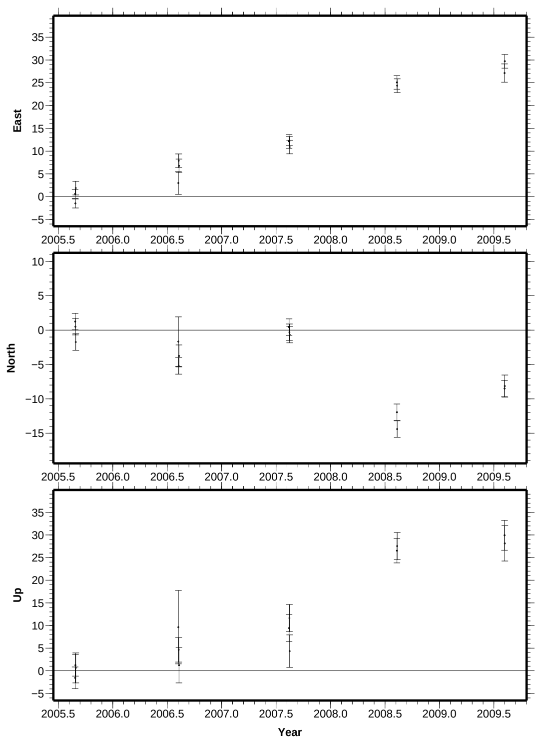
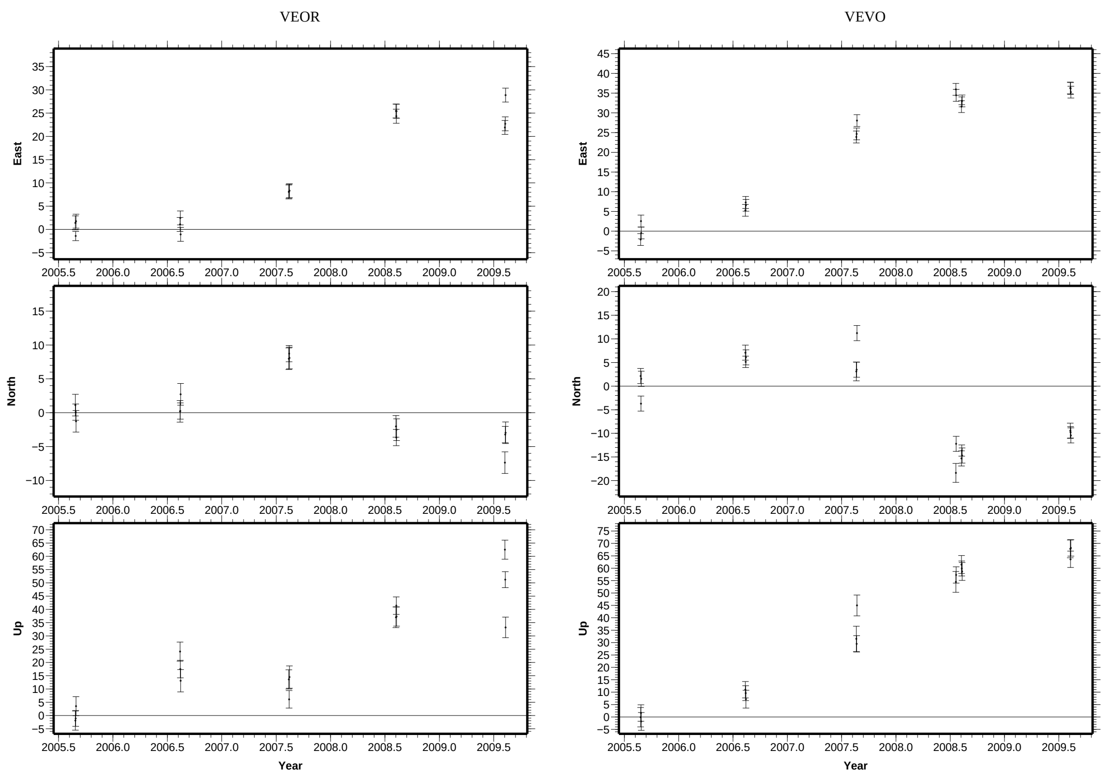


TUNG




VEOR
VEVO
East
North
Up
Year
2005.5
2006.0
2006.5
2007.0
2007.5
2008.0
2008.5
2009.0
2009.5