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The recognition of transient compressional fault slow-slip along the northern shore of Hornsund Fjord, SW Spitsbergen, Svalbard

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Abstract: This paper presents the results of direct 3-D fault displacement monitoring along the northern shore of Hornsund Fjord, SW Spitsbergen, Svalbard. The fault displacements have been recorded using three permanently installed optical-mechanical crack gauges since 2009. The monitoring data from all three sites provided evidence for a remarkable slip event that lasted from September 2011 to May 2012. The cause is discussed in some detail with consideration given to both exogenic (temperature changes, surface processes) and endogenic processes (isostatic rebound and regional seismicity). It is proposed that transient fault slips recorded had a tectonic origin and were caused by approximately W-E oriented compression corresponding to regional compression in the Svalbard area.

Key words: Arctic, Svalbard, Hornsund, 3-D fault displacement monitoring, transient slow fault slip.

Introduction

The EU TecNet fault displacement network was established more than ten years ago to record three-dimensional displacements across selected tectonic structures within the shallow crust (Stemberk *et al*. 2003). The network, which consists of more than one hundred fifty sites spread across the globe is managed by the Institute of Rock Structure and Mechanics of the Czech Academy of Sciences (www.tecnet.cz). The data obtained have showed that long periods of tectonic "quiescence" were alternated with shorter periods of increased fault activity. It was discovered that these periods of increased activity occur contemporaneously along distinct tectonic units and that they are caused by endogenic processes

(Stemberk *et al*. 2010; Briestenský *et al*. 2014). The increased displacements reflect periods of the widespread tectonic redistribution of stress and strain within the shallow crust (Košťák *et al*. 2007, 2011).

The EU TecNet network includes also three northernmost sites in Svalbard that are located along the northern shore of Hornsund Fjord, SW Spitsbergen. In the light of the fault kinematic gathered from the vicinity of the Polish Polar Station Hornsund in 2009, three fault locations were selected for displacement monitoring. The selected faults were monitored using the TM-71 optical-mechanical crack gauges (Košťák 1991; Klimeš *et al*. 2012) since July 2009. The main focus of this contribution is to present the results of recent fault monitoring and to discuss the possible processes responsible for the displacements.

Geological setting of southern Spitsbergen

The geological setting and tectonic history of Spitsbergen was previously published by Birkenmajer (1972a, b), Harland (1969, 1997) or Hjelle (1993). The study area lies within the West Spitsbergen Fold-and-Thrust Belt (WSFTB), a tectonic zone affected by early Paleogene deformation. The WSFTB formed along the transform plate boundary between Greenland and the western Barents Sea during Paleocene–Eocene breakup in the North Atlantic (*e.g*. Talwani and Eldholm 1977; Faleide *et al.* 2008). Approximately 10–40 km margin-perpendicular shortening (*e.g*. von Gosen and Piepjohn 2001) accumulated in the WSFTB is usually attributed to transpression and strain partitioning in a restraining bend (Harland 1969; Lowell 1972; Bergh *et al.* 1997) or to a succession of tectonic events with orthogonal compression during a first stage and dextral strike-slip faulting during a second stage (CASE-Team 2001; Piepjohn *et al.* 2012). The rejuvenation of old extensional structures in the northern part of Spitsbergen during the late Cenozoic and Quaternary resulted in highly restricted volcanic activity (Dallmann 1999). However, no volcanic rocks of that age are known from southern Spitsbergen, where the study area is located. Local directions of recent plate motion for this region were derived from kinemetric models (*e.g.* DeMets *et al.* 1990, 2010). They show that the Barent's shelf in this region is moving southeastwards at an azimuth of about 136°.

The 1:25 000 geological map of the Hornsund area (Czerny *et al.* 1993) shows a set of NNW-SSE normal faults that dip to the WSW. These faults represent the youngest structures within the local tectonic framework. Czerny *et al.* (1993) described a significant fault that can be traced in the western part of Fugleberget, close to the Polish Polar Station, with a throw exceeding 1000 m. Moreover, other faults with smaller throws were recognised between Angellfjelet and Revdalen. However, the most significant and well-known structure hereabouts is the Kongsfjorden-Hansbreen Fault Zone. This structure crosses Hornsund Fjord in a N-S direction and separates two terranes that were originally parts of east and north Greenland (Harland and Wright 1979).

The recent and ongoing geodynamic activity of Spitsbergen is reflected by high heat-flow and seismicity. Hjelle (1993) suggested that the thermal springs and volcanoes were associated with the presence of a large magma chamber located beneath Svalbard. Abnormally high temperature springs have been identified in the areas north of Svalbard where noticeably strong heat flow was measured at sea (Hjelle 1993). Two thermal springs, which may be related to the high geothermal gradient known from northern Spitsbergen, were discovered around Hornsund, close to the eastern part of Torellbreen, in 1982 (Migała and Sobik 1982). The water temperatures were 12.3°C and 6.5°C in the air temperatures of -14.5°C and -12°C, respectively. Furthermore, earthquake focal mechanism analyses found that all fault-plane solutions are consistent with a stress field characterised by E-W compression in Svalbard, varying between N 62°E and N 110°E (Mitchell *et al.* 1990). Similar results were previously obtained from *in-situ* stress measurements in central Spitsbergen (Hast 1969). It was concluded that the maximum principal stress has a horizontal component with a strike of N 102°E. The broad agreement that exists between the two studies indicates that the direction of the maximum principal stress axis is approximately E-W throughout Svalbard.

In the area around Hornsund weak shock foci have been identified close to the Polish Polar Station with hypocentres at depths of approximately 10 km (Górski 1986). The recorded earthquakes appear to be associated with active E-W trending faults within the Hornsund Fjord crossing the main NNW-SSE striking fault system (Górski 1997; Górski and Teisseyre 1991). The last significant event in Svalbard, with M = 6.1, occurred on February 21, 2008. This event represents the strongest registered earthquake in Svalbard's history. Its epicentre was located about 140 km southeast of Longyearbyen in Storfjorden (Pirli *et al.* 2010). An aftershock sequence after the February 2008 main shock finished in July 2012 (Pirli *et al.* 2013). Junek *et al*. (2014) compiled moment tensor solutions for aftershock sequence to quantify the direction of maximum horizontal stress for region. They concluded that this direction does not align with the local direction of plate motion however mechanisms of aftershocks are consistent with stress field oriented generally E-W. It corresponds to previous finding of Hast (1969) and Mitchell *et al.* (1990).

During 2012, an increase of seismic activity was recorded within the Arctic Circle. During the monitoring period outlined herein the strongest and most closely situated earthquake occurred on February 8, 2012 with a magnitude of M = 5.2 (earthquake.usgs.gov). The epicentre was located at 76.848°N, 7.323°E, 212 km WSW from the monitoring network at Hornsund, along the Mid-Atlantic Ridge. Another strong earthquakes, with M = 7.7 and M = 7.6, occurred in the Sea of Okhotsk near northeast Russia on August 14, 2012 (emsc-csem.org) and near

Jan Mayen Island on August 31, 2012 (Lin 2013), respectively. The latter had a depth of 9.9 km and was followed by aftershock of M = 5.2.

The present day geodynamic activity across Svalbard is studied by GPS and by gravity monitoring at the Ny-Ålesund site. This research is focused on understanding the effects of postglacial isostatic uplift. Both the GPS and gravity data show significant non-linear changes through time (Kierulf *et al.* 2009; Omang and Kierulf 2011). Since 2001, an average rate of uplift has been 8.5 mm/yr, considerably higher than the rate of 4.7 mm/yr predicted by geophysical models. The period 2003–2006 was characterised by an anomalously high uplift rate of 11.2 mm/yr which is two and a half times more than the previously recorded rate, of 4.8 mm/yr. The cause of increased rate of uplift remains unexplained. Kumar and Singh (2012) discussed some preliminary GPS monitoring results from the Ny-Ålesund site and suggested that the recorded movements not only reflected isostatic rebound but also recent active tectonics in western Svalbard.

Fault displacement monitoring

Methodology. — The TM-71 optical-mechanical crack gauge (Fig. 1) is used for the precise three-dimensional measurement of relative movement across a discontinuity that separates two blocks. The advantage of this type of monitoring is that it is able to record fault displacement data in three-dimensions (Košťák 1991; Klimeš *et al.* 2012; Martí *et al.* 2013). The instrument records data on the basis of optical-mechanical interferometry via the generation of moiré patterns, which result from the bending and interference of light rays as they pass through two specially designed optical grids. Because this is a manual instrument, it does not need any electrical supply and, therefore, it is very suitable for long-term monitoring in harsh environmental conditions. It can be left for many years in the field without loss of the total displacement results (Briestenský *et al.* 2011). Information about the specific movements is represented by the moiré patterns, which are mathematically transformed into three-dimensional displacement vectors and angular rotations (see *e.g.* Martí *et al.* 2013). The resolution of the instrument varies between 0.05 and 0.007 mm, depending on the line density of the spiral within the optical grid. The three Hornsund instruments record displacements with a resolution of 0.0125 mm and the rotations can be measured with a resolution of $3.2 \cdot 10^{-4}$ rad (-0.018°).

The data are usually recorded manually using a digital camera with a frequency of once per month. The advantages and limitations of the instrument are well defined given the protracted installation at a number of sites in, for example, the Czech Republic, Slovenia, Slovakia, and Poland (Kontny *et al.* 2005; Gosar *et al.* 2009; Šebela *et al.* 2009). It has been shown that seasonal and climatic variations can be detected and separated from the recorded movements (Briestenský *et al.* 2010). It is

Fig. 1. The TM-71 optical-mechanical crack gauge located in front of the Hansbreen Glacier at Site 1 (Photo by T. Nýdl). The monitored fault 82°/225° crosses the outcrop beneath the instrument.

possible, therefore, to obtain accurate records of ongoing gravitational processes or tectonic activity. The suitability of this instrument for geodynamic monitoring has been additionally corroborated by comparisons with the results obtained using other geophysical methods (Košťák *et al.* 2011).

Three TM-71s were installed in the area around Hornsund in July 2009 (Figs 1–2):

- Site 1 (77°00.789N, 15°35.974E): This instrument is situated in the Baranowski Peninsula in front of the Hansbreen Glacier across a NW-SE striking fault (82°→225°; dip→dip direction). The fault cuts a sequence of quartzites and is filled by crushed black schists of the Eimfellbreene Formation.
- Site 2 (77°00.447N, 15°35.731E): This instrument is situated close to Site 1 in the Baranowski Peninsula across a NNE-SSW striking fault (89°→110°). The fault cuts schists with a width of about 10–15 cm and is filled by crushed and clayed rock of the Ravdalen Formation.
- Site 3 (77°00.024N, 15°23.563E): This instrument is situated about 5 km to the west of Sites 1 and 2 at Worcesterpynten. The instrument was installed across a WNW-ESE striking sub-vertical trench with a width of 1 to 2 m and a length of several hundred meters that cuts the paragneisses of the Skoddefjellet Formation.

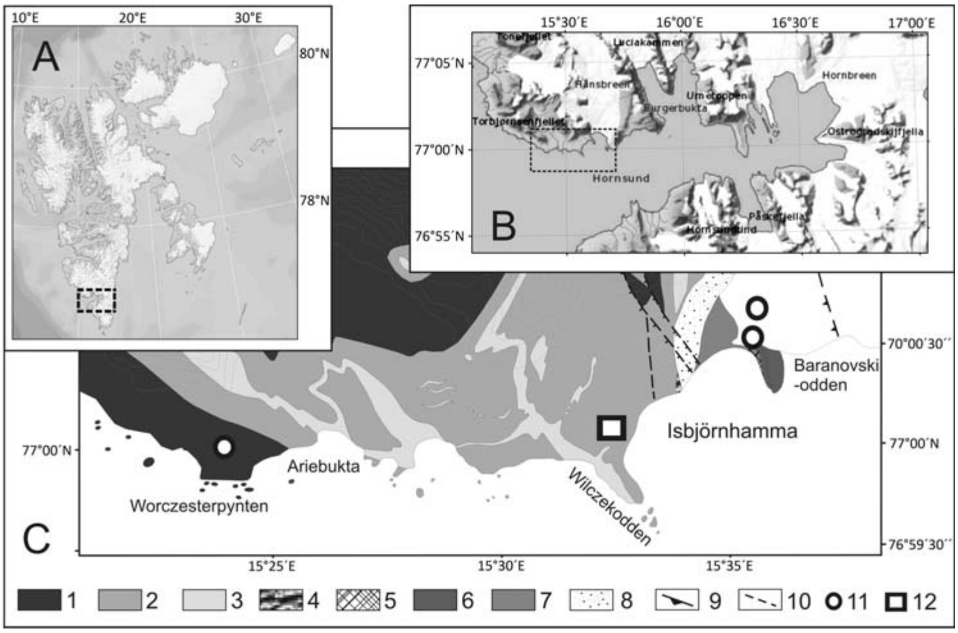

Fig. 2. The location of the monitoring sites within their geographical and geological setting. **A**. The location of Hornsund Fjord in Svalbard. **B**. The study area near the Polish Polar Station on the northern shore of Hornsund Fjord. **C**. A geological sketch of the study area. 1 – Skoddefjellet Formation; 2, 3 – Ariekamen Formation; 4 – Ravdalen Formation; 5 – Eimfellbreane Formation; 6 – Skålfjellet Formation; 7 – fluvial and marine deposits; 8– moraines; 9 – thrust faults; 10 – faults; 11 – TM-71s; 12 – Polish Polar Station, Hornsund.

Displacement monitoring results. — During the first two years of monitoring, no remarkable displacements were recorded, but the activity has increased significantly since September 2011. The extraordinary displacements occurred synchronously at all three sites (Fig. 3). This period of enhanced tectonic activity lasted from September 2011 until May 2012. The period can be divided into two separate events as the vertical displacements appear to reflect two distinct transient vertical pulses. Thereafter, no remarkable displacements were recorded until September 2014. The results obtained at each of the three sites are detailed below:

Site 1

The long-term fault development recorded during five years of monitoring (Fig. 3):

- horizontal fault dilation – fault opening trend of 0.5 mm/4 years;
- horizontal strike-slip – no significant trend; affected by minor peak-to-peak amplitude (with its peak during the winter season);
- vertical displacements – the overall trend shows subsidence of the northeastern block (0.6 mm/4 years), which is affected by a peak-to-peak amplitude of 0.3 mm (with its peak during the summer season).

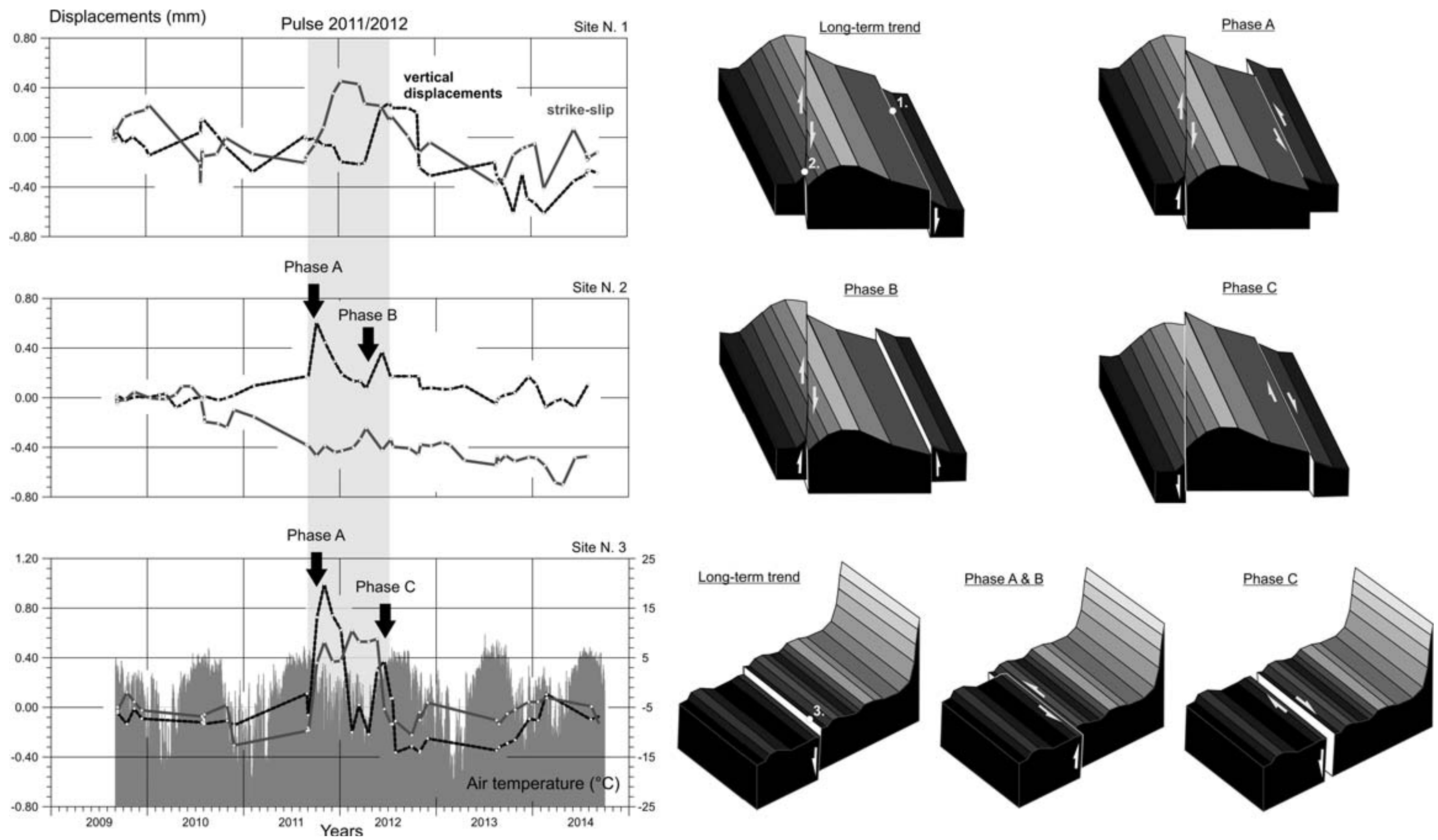

Fig. 3. The fault displacements (vertical component: interrupted black line; strike-slip: continuous grey line) recorded at all three monitored localities in the area around northern Hornsund: the grey shading highlights the period with increased dynamics activity (tectonic pulse). Block diagrams show a schematic model of long-term block movements and short-term movements during the pulse 2011/2012.

The recorded long-term displacements can be characterised as oblique dextral subsidence of northeastern block/oblique dextral uplift of the southwestern block in an extensional regime. However, a remarkable sinistral strike-slip displacement of 0.65 mm began in September/October of 2011 and vertical northeastern block reverse displacement corresponds to relative uplift began in April/May 2012. The magnitudes of the short-term displacements exceeded the peak-to-peak amplitudes caused by seasonal massif dilation. These movements were both contrary to the long-term displacement trend and contrary to other years of monitoring.

Site 2

The long-term fault development recorded during five years of monitoring (Fig. 3):

- horizontal fault dilation – no significant trend nor peak-to-peak amplitude;
- horizontal strike-slip – dextral trend of 0.5–0.6 mm/4 years;
- vertical displacements – no significant trend.

The recorded long-term displacements can be characterised as slight dextral strike-slip along the fault without an accompanying vertical component. However, two significant vertical displacements were recorded in the same time as those events described previously at Site 1. The first displacement caused 0.5 mm uplift of the western block in September/October 2011, while the second one caused 0.3 mm uplift of the western block in April/May 2012. Both of these vertical displacements were reversed.

Site 3

The long-term fault development recorded during five years of monitoring (Fig. 3):

- horizontal fault dilation – no trend is apparent but the displacements are affected by peak-to-peak amplitude of up to 1.1 mm;
- horizontal strike-slip – no significant trend;
- vertical displacements – the overall trend shows subsidence of the southwestern block (0.4 mm/4 years).

Two vertical displacements were observed during 2011 and 2012 years, and these both events had opposite displacement sense comparing with the long-term trend. Moreover, both were accompanied by significant strike-slips. The first displacement showed sinistral oblique-slip southwestern block uplift (vertical slip of 1.2 mm, strike-slip of 0.7 mm) in September/October 2011, while the second presented dextral oblique-slip southwestern block uplift (vertical slip of 0.6 mm, strike-slip of 0.7 mm) in April/May 2012. Both these vertical displacements as well as the strike-slip displacement were reversed.

Summary of recorded fault displacement. — The recorded long-term (2009–2014) displacement regime has a significant extensional character, documented by fault opening and subsidence (Figs 3–4). The monitoring data, however, also show

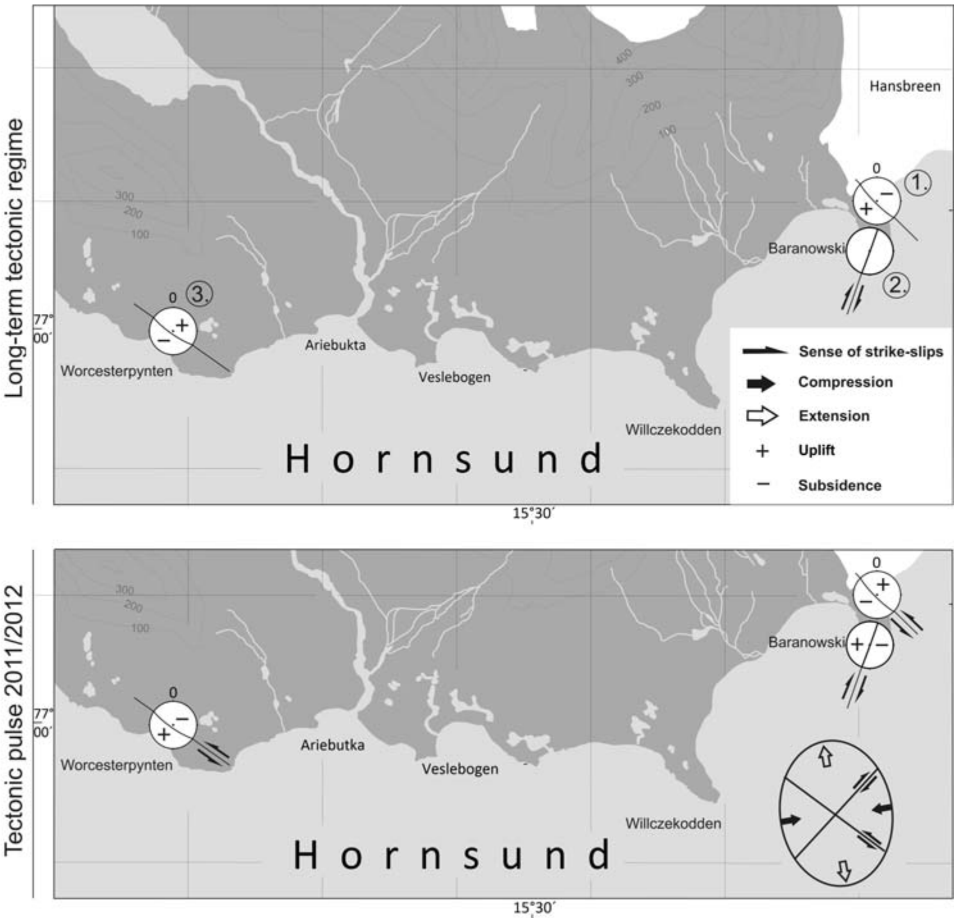

Fig. 4. Schematic horizontal projections of the long-term tectonic regime and short-term tectonic pulse 2011/2012 as defined by the three faults monitored in the Hornsund area.

that this regime can be rapidly modified, to attain a compressional character as the strike-slip displacements cannot be separated into two distinct events. It appears, therefore, that, unlike the vertical displacements, which are usually affected by gravitational forces, the results reflect one significant event lasting from September 2011 to May 2012 (Figs 3–4). Alternatively, the whole event could be divided into three phases (A, B, C). The first two phases represent compressional stages and the following phase C reflects stress relaxation (Fig. 3). A causative stress field (maximum of compression) had the E-W or WSW-ENE orientation (Fig. 4). This approximately E-W oriented compressional regime has also been identified previously from *in-situ* stress measurements (Hast 1969) and local earthquake fault-plane solutions (Mitchell *et al.* 1990; Junek *et al.* 2014). As shown here, this compressional regime, which lasted no more than a year, was observed during the study period.

Discussion

There are several processes that may affect the fault displacement results, the most significant of which are temperature changes, surface processes, postglacial isostasy, and seismicity.

Temperature influence. — The majority of EU TecNet sites are located in caves or other underground spaces in order to minimise the influence of daily or seasonal temperature changes on the recorded data. The instruments in the Hornsund area are located at the surface. Consequently, the recorded data reflect not only endogenic processes but also exogenic processes related, for example to thermal expansion. These exogenic factors affect not only the rock massif itself but also all components of the instrument (Briestenský *et al.* 2010). The recorded fault displacements, therefore, display peak-to-peak amplitudes, which mask the underlying displacements of very low magnitude or trends. Not all of the results, however, obtained from the Hornsund area, have been affected by the massif dilations. There are visible peak-to-peak amplitudes in both the strike-slip and vertical components recorded at Site 1. They accelerated during the aforementioned event in 2011/2012.

Regarding to seasonal changes of temperature, their range is relatively narrow during the year, up to 25°C and relatively stable during each season (up to about 5–10°C during polar day and up to 10–20°C during polar night). As demonstrated in Fig. 3 and Table 1, there is no evidence that temperature variation was different during 2011/2012 in contrast to other year of monitoring. It seems then that the extraordinary amplitude recorded during this year was unlikely to have been the result of thermal elastic deformation.

Table 1

Maximal, minimal a and mean air temperature recorded in Hornsund 2009–2014

Year	Max. temperature (°C)	Min. temperature (°C)	Annual mean temperature (°C)
2009	4.8	and17.6	-5.5
2010	2.7	-22.2	-11.6
2011	3.1	-19.8	-6.6
2012	2.8	-23.7	-7.9
2013	5.6	-20.0	-8.1
2014	-0.1	-20.6	-9.6

Surface processes. — All the observation sites were located on the metamorphic basement outcrops (quartzites, crystalline shists, paragneisses) without a Quaternary cover. They were situated close to the sea on a relatively flat surface at an altitude up to 10 m a. s. l. According to our field studies and those of previous (Karczewski *et al*. 1984; Birkenmajer 1990; Czerny *et al.* 1993), indicate that none of the installed site locations show evidence for any significant gravitational block movements or permafrost creep.

Postglacial isostasy. — The area around Hornsund is characterised by some of the lowest postglacial emergence in Svalbard (Forman *et al.* 2004). Birkenmajer and Olson (1970) estimate to have been no more than 5 metres in the last 5 ka. The Mid-Holocene glacial episode at about 2.5–3 ka, termed the Revdalen Stage (Karczewski *et al.* 1981; Lindner *et al.* 1986), has been defined by younger morainic ramparts and by glacial sediments in Revdalen (Lindner and Marks 1993). The subsequent warming is evidenced by fossil flora in the forefields of the Werenskiold and Hans Glaciers. This flora was dated at 1.5–0.7 ka and 2.1 ka, respectively (Pękala 1989), and it is thought that the raised beach at 4.5–6 m a.s.l. formed contemporaneously (Lindner *et al.* 1991). The geodetic observatory at Ny-Ålesund has been recording GPS measurements since 1991 while a superconducting gravimeter to monitor the effect of present-day ice melting and glacial isostatic adjustment was installed in 1999 (Mémin *et al.* 2011). The results have shown that the mean isostatic uplift rate is around 8.5 mm/year while the rate of uplift from 2003 to 2006 was two and a half times greater than it had been during the preceding period (11.2 mm/year against 4.8 mm/year) see Kierulf *et al.* (2009), Omang and Kierulf (2011). However, while it might be tempting to suggest that the recorded anomalous slips reflect postglacial isostasy, the GPS data suggest that postglacial isostatic uplift is characterised by non-linear vertical movements. The fault displacement trends reported in this paper had significant strike-slip components while the vertical components were reversed during the event between September 2011 and June 2012. This fact is inconsistent with the isostatic hypothesis. Moreover, it should be mentioned that the period of uplift acceleration between 2003 and 2006 corresponds to the observed period of high geodynamic activity recognised by fault displacement (mostly vertical acceleration) across continental Europe (Stemberk *et al*. 2010; Košťák *et al*. 2011).

Local and regional seismicity. — During the monitoring period the strongest and most closely situated earthquake occurred on February 8th 2012 about 212 km to the WSW from the Hornsund monitoring network, along the Mid-Atlantic Ridge. The earthquake occurred in the middle of the observed fault displacement pulse and was coeval with the strike-slip movement maxima recorded at Sites 1 and 3 (Fig. 3). However, the pulse began about half a year before the earthquake similarly to continental Europe, where it was reported that extraordinary displacements predate strong local earthquakes by about the same length of time (Briestenský *et al*. 2007; Košťák *et al.* 2007; Stemberk and Košťák 2008; Stemberk and Hartvich 2011). Briestenský *et al.* (2007) also concluded that peak-to-peak amplitude affecting strike-slip component can be accelerated or disrupted during nearby earthquake events. These lines of evidence lead it to be suggested here that the displacements in the Hornsund area could reflect contemporaneous tectonic processes associated with spreading along the Mid-Atlantic Ridge. Stemberk *et al.* (2010) and Briestenský *et al.* (2014) have described similar recorded pulses.

Conclusions

The 3-D fault displacement monitoring in Hornsund Fjord has shown that the locally prevailing long-term extensional regime can be rapidly modified by a short-term compressional event with a principal horizontal stress axis oriented approximately W-E to WSW-ENE. Such a change was observed between September 2011 and May 2012. Furthermore, the compression orientation matches with previously published *in-situ* stress measurements and fault plane solutions from Svalbard. It is suggested that this stress reconfiguration resulted from deep seated processes operating within the lithosphere-asthenosphere most likely reflecting ridge push from the Mid-Atlantic spreading centre that was manifested by the earthquake with M = 5.2 on 8th February 2012.

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