European volcanological supersite in Iceland:
a monitoring system and network for the future

Report

D5.7 – Ice evolution Time series of elevation changes during caldera collapse and geothermal activity in Iceland

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Summary

This deliverable report presents results of studies carried out by Nordvulk, Institute of Earth Sciences, University of Iceland (UI), and the German Space Agency (DLR) on ice changes related to geothermal and volcanic activity in Iceland. Geothermal activity that remains subglacial leads to basal melting and formation of depressions on the ice surface above the thermal anomaly. A less frequent type of activity is caldera collapse, and it is a remarkable coincidence that such an event should happen at Bárðarbunga during the FutureVolc project. The subsidence was monitored and here a series of maps made from TanDEM-X satellite data are presented, showing the evolution of the ice surface changes during collapse from August to 8 November 2014. The data show that by 8 November volume of subsidence was close to 1 km^3, the average subsidence was 16 m and the maximum about 50 meters. For subglacial geothermal activity, the term ice cauldron is used for depressions above the heat sources, regardless of whether they are shallow and crevasse free or deep and heavily crevassed. A system consisting of sub-meter differential GPS and a ground clearance radar altimeter on board the surveying aircraft of Isavia, the Icelandic civil aviation service, has been used to monitor changes in glaciers due to geothermal and subglacial volcanic activity for the last 17 years. Here the data obtained for the Skaftárkatlar geothermal areas in northwest Vatnajökull and the Katla caldera are presented. The data for the Skaftárkatlar reveal the characteristics of the cauldrons in terms of size of subsided area, the amount of subsidence and thickness and extent of the subglacial water body during draining events which cause jökulhlaups in river Skaftá. All data for the nine regularly surveyed flight traverses in the Katla caldera are presented. The results on geothermal activity are summarised, showing a peak in geothermal activity in 1999, another in 2004-2006 and the third peak in 2011. All these peaks are associated with increased seismicity and ground deformation. Sudden, unexpected jökulhlaups from underneath ice cauldrons occurred in 1999 and 2011. In the near future, the aircraft profiling may partly be superseded by satellite methods that extract surface maps using SAR or optical methods. The main strength of the aircraft based system is its flexibility, fast delivery of information (2-3 m absolute elevation accuracy) with a few hours processing delay, and that it is free from the present constraints of satellite repeat times.

Contents

1 Introduction

This deliverable report 5.7 of FutureVolc describes observations of ice evolution related to volcanic and geothermal activity in Iceland. Three specific examples are covered: (1) the subsidence of the Bárðarbunga caldera in 2014-15, as studied through TanDEM-X satellite mapping of the glacier surface covering the caldera, and observations at geothermal ice cauldrons within glaciers of the volcanic zone in Iceland. The examples shown are (2) the Katla caldera and (3) the Skaftárkatlar geothermal area in northwest Vatnajökull. Observations used for (2) and (3) are principally profiling with an aircraft-based system consisting of air clearance altimeter and differential sub-meter GPS (Gudmundsson et al., 2007). Chapters 2-4 cover background information for monitoring of ice cauldrons, Chapter 5 presents results on Bárðarbunga subsidence from TanDEM-X and Chapters 6 and 7 contain results for the subglacial geothermal areas of Skaftárkatlar and Katla, including plots of all profile data for the latter location (1999-2015).

2 Geothermal areas in glaciers

A substantial part of the volcanic zones in Iceland is covered by glaciers (Figure 1). This includes the very active volcanic systems of Grímsvötn, Bárðarbunga and Katla and their central volcanoes. Other central volcanoes that have partial to full ice cover are Öræfajökull, Þórðarhyrna, Kverkfjöll, Hamarinn, Eyjafjallajökull, Hofsjökull, Prestahnjúkur and Langjökull. Minor ice cover is found at Hekla, Torfajökull and Tindfjallajökull. In addition a large geothermal area is located between Hamarinn and Grímsvötn, manifested in two large ice cauldrons, the Eystri Skaftárketill and Vestari Skaftárketill (eastern and western Skaftá Cauldrons).

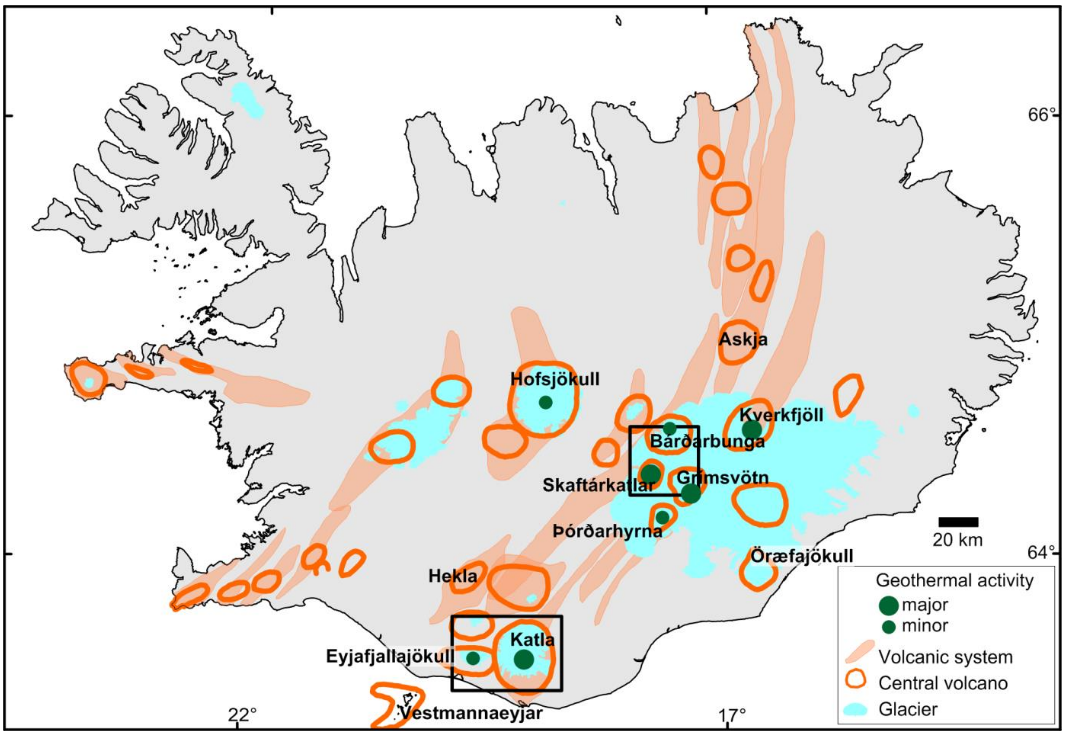


Figure 1. Volcanic systems and central volcanoes in Iceland (modified from Jóhannesson and Saemundsson, 1998). The margins of maps shown on Figures 5 and 10 are indicated.

Signs of geothermal activity are found at many of these ice covered areas, manifested as ice cauldrons. The term ice cauldron is used to denote depressions in glaciers formed by melting at the base by geothermal or volcanic activity (Björnsson, 1976; Jarosch and Gudmundsson, 2006). These depressions are usually circular or elliptical in form and the depth can range from 5-10 metres to over 200 metres. Ice cauldrons often have concentric crevasses around the margins, and the deeper ones can be holes with almost vertical walls. They can be classified into cauldrons where water accumulates at the glacier base or cauldrons where meltwater drains continuously away. The latter is the most common form and most small ice cauldrons drain continuously. The accumulating cauldrons show considerable variations in their depth, sometimes displaying a regular pattern of accumulation and rise in bottom height that is truncated by sudden drainage in a jökulhlaup. The two Skaftár cauldrons are of this type while most of the cauldrons in the Katla caldera are of the continuous drainage type (Gudmundsson et al., 2007).

The importance of monitoring regularly the size and depth of cauldrons has implications for short to medium term hazard assessment and the related issue of early warning. The principal situations that arise are:

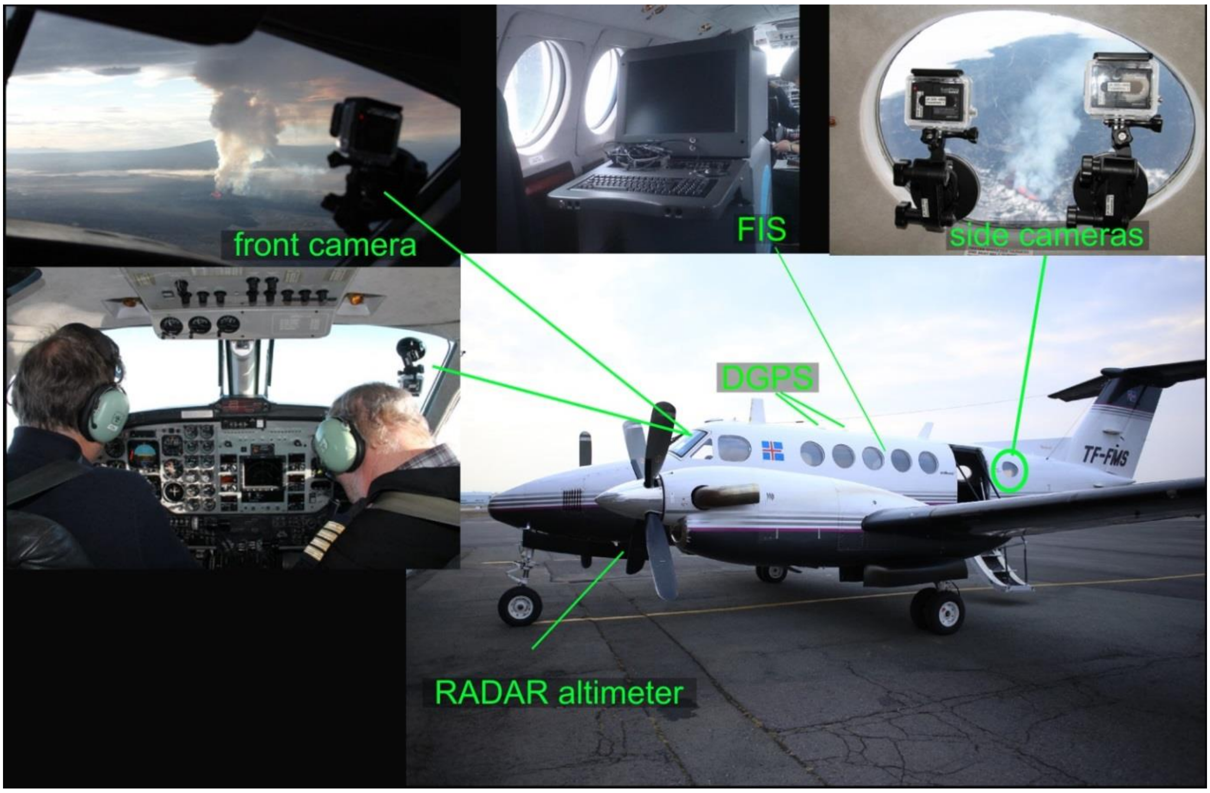
Variations in heat source (with examples):

a) Geothermal activity increasing
   - Deepening of cauldron – implies increased melting at base and continuous drainage (several examples from Katla)
   - Shallowing of cauldron – may indicate meltwater accumulation under cauldron (e.g. cauldron 16 in Katla before jökulhlaup on 9 July 2011).
b) Geothermal activity decreasing
   - Shallowing of cauldron – decreased melting leads to ice flow into cauldron exceeding melting and drainage. It may be difficult to differentiate between this scenario and meltwater accumulation under the cauldron (several examples from Katla).
c) Volcanic eruption under ice
   - Little or minor change in surface – indicates that meltwater is not escaping from cauldron and both meltwater and erupted products are accumulating (observed in Eyjafjallajökull, Magnússon et al., 2012).
   - Rapidly increasing depth – rapid drainage of meltwater from cauldron (Gjálp 1996, Gudmundsson et al., 1997).

Variations in meltwater volume beneath ice cauldron:

a) Slow rise in cauldron bottom – indicates water accumulation (Skaftárkatlar, occasionally with cauldrons in Katla).
b) Rapid subsidence of cauldron (drop in level occurs over hours to days) drainage in a jökuhlaup (Skaftárkatlar).

Other variations are possible, but the above are considered the most common, and all have been observed in the last two decades.



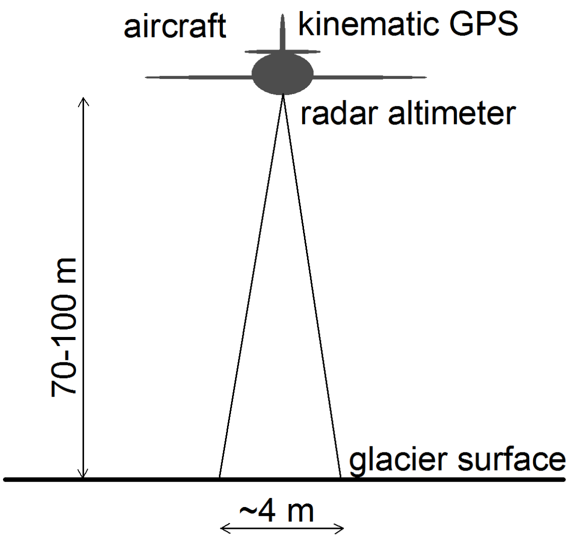


Figure 2. Upper: Surveying aircraft of Isavia with installations of surveying equipment for monitoring, including the radar altimeter used for surface profiling (from Gudmundsson et al. 2015, Deliverable 7.2). Lower: geometry of altimeter beam spreading at optimal flying height of 70-100 m (after Gudmundsson et al. 2007).

3 Surveying system

The system used for surveying the profiles is installed on board the Isavia (Icelandic Civil Aviation Service) surveying aircraft, a twin engine Beechcraft 200 Super King Air (Figure 2). The system consists of a real time differential GPS Omnistar sub-meter system and an air clearance analogue Collins ALT-50 radar-altimeter, operating at 4300 MHz with an error of 2% (Gudmundsson et al., 2007). The radar-altimeter transmits pulses four times a second. It has a range of 0-995 m but in order to obtain the best accuracy, the aircraft is flown below 150 m ground clearance. Nominal conditions are achieved when flying at 70-100 m height in calm conditions, when absolute accuracy is 2-3 meters and relative accuracy within profile 1-2 m.

4 Glacier surface surveying

Aircraft observations at Bárðarbunga in 2014-15 could be compared with surface KGPS profiling. It showed that for the cold and dry conditions experienced at Bárðarbunga in winter the radar-altimeter signal penetrates the dry snow layer and reflections are obtained from a depth similar to the location of the zero degrees surface in the firn. This penetration amounted to 6-7 m in late winter for Bárðarbunga (surface elevation ~1900 m a.s.l). For the lower and warmer Mýdalsjökull (surface elevation 1300-1490 m a.s.l.), overlying the Katla caldera a systematic penetration of the surface of this magnitude has not been detected. This suggests that frequent formation of ice lenses in the firn resulting from short-lived periods of thaw at Mýrdalsjökull at various times at winter generates reflectors that are close to the surface (~1-2 m). This penetration is a subject of further research. However, it should not significantly affect relative depth observations of cauldrons, since depth penetration should not vary significantly between a cauldron and its surroundings. This depth penetration is not seen in summer as demonstrated by close correspondence between surface profiling and aircraft altimeter profiling at Katla in September 2000 (Gudmundsson et al., 2007).

An important consideration is that the profiling data is ready during flight, as the GPS correction is real time and the recording system on board TF-FMS delivers profiles with coordinates and heights. Processing is therefore limited to extracting the data and display them in a suitable form. This allows results to be presented within a few hours if needed.

5 Bárðarbunga caldera subsidence in TanDEM-X RawDEMs

The TanDEM-X dataset is composed of 5 bistatic acquisitions covering the Bárðarbunga caldera, two before the caldera collapse and eruption in Holuhraun (01.08.2014, 12.08.2014) and three during the caldera subsidence and eruption (17.10.2014, 28.10.2014, 08.11.2014). To calibrate the raw DEM stack, the operationally calibrated and mosaicked TanDEM-X DEM has been employed. This model is generated using several acquisitions and IceSAT points as reference. A single tile is spanning 1 square degree, and it is sufficient to cover the scenes in the stack. The acquisitions are fully covering the Bardarbunga caldera and the north-western part of the Vatnajökull glacier.

To evaluate the topographical changes, the DEMs are generated over a fixed geographical grid with spacing of about 6 m in latitude and longitude. The original interferogram resolution, computed taking into account the independent number of looks and the SAR cell resolution, is about 9 meters.

The DEM differences between the reference DEM and all the others are depicted in Figure 3. The most prominent topographical change is the caldera subsidence, originated by the collapse of part of the ground above the magma chamber. The considerable depression left in the landscape, with subsidence maximum exceeding 50 m for the largest time lag in Figures 3-4, is well visible. The formation of ice cauldrons at the south-eastern rim of the caldera is also noticeable. Moreover, the differential maps reveal the complete topographical changes over the imaged part of the Vatnajökull glacier. Among them, increases in surface elevation within the eastern Skaftá cauldron and the Grimsvötn caldera are conspicuous, considered to result from uplift of the glacier surface due to water accumulation in these well-known geothermal areas (e.g. Björnsson, 2003).

The result of a quantitative study on the caldera subsidence is displayed in Table 1. SAR backscatter is measured by calibrating the amplitude signal and compensating for the local incidence angle. The mean caldera backscatter is given in the second column of Table 1. The difference between summer and autumn backscatter has been already analysed in the previous paragraph. The mean coherence over the caldera given in the third column is in general very high and the relative height error in the fourth column is low. The caldera collapse is evaluated in terms of mean height and volume changes in the fifth and sixth column of Tab.1 respectively. These mean values represent the average change over the caldera. For the last stack acquisition, 69 days after the main fissure opening, the caldera the mean subsidence had reached 16 meters, while the maximum subsidence was about 50 m in its north-eastern part, and with an impressive volume loss of about 1 km^3. This yields a mean rate of change, averaged over the whole caldera of about 1 meter per week.

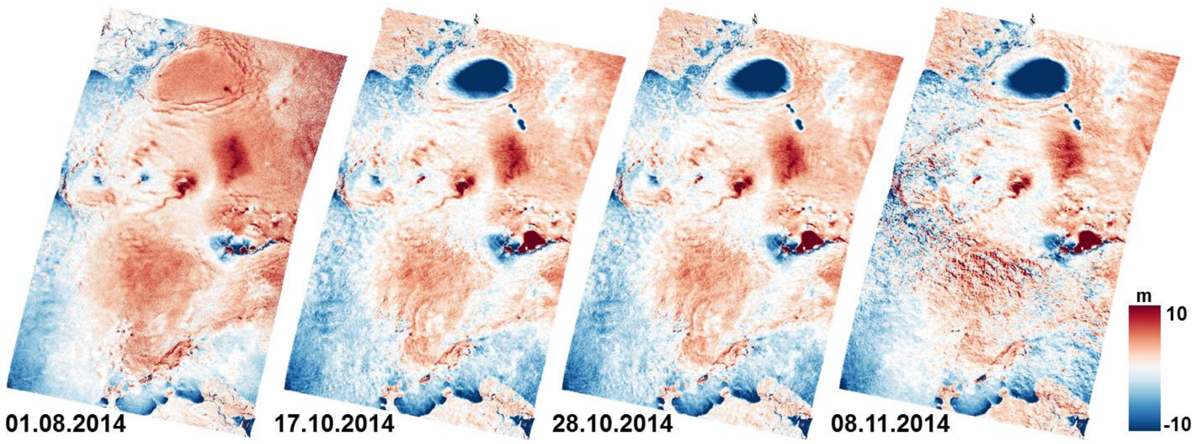


Figure 3. Height changes of several RawDEMs with respect to the final TanDEM-X DEM.

Table 1: Summary of measurement extracted from the TanDEM-X RawDEM Stack.

	Backscatter [dB]	Coherence	Height Error [m]	DEM diff - ref [m]	Vol diff - ref [m3]	DEM diff - Aug [m]	Vol diff - Aug [m3]
Aug 1	-15.23 ± 0.86	0.90 ± 0.03	1.34	4.53 ± 1.38	2.88e8	-	-
Aug 12	-15.31 ± 0.75	0.90 ± 0.03	1.70	5.05 ± 1.37	3.21e8	0.52	0.33e8
Oct 17	-9.86 ± 0.74	0.96 ± 0.01	0.63	-9.32 ± 10.32	-5.93e8	-13.85	-8.81e8
Oct 28	-9.75 ± 0.76	0.96 ± 0.01	0.55	-10.60 ± 11.23	-6.74e8	-15.13	-9.62e8
Nov 8	-9.60 ± 0.77	0.94 ± 0.01	0.69	-11.86 ± 12.24	-7.54e8	-16.39	-10.4e8
Reference	-	-	0.67	-	-	-4.53	-2.88e8

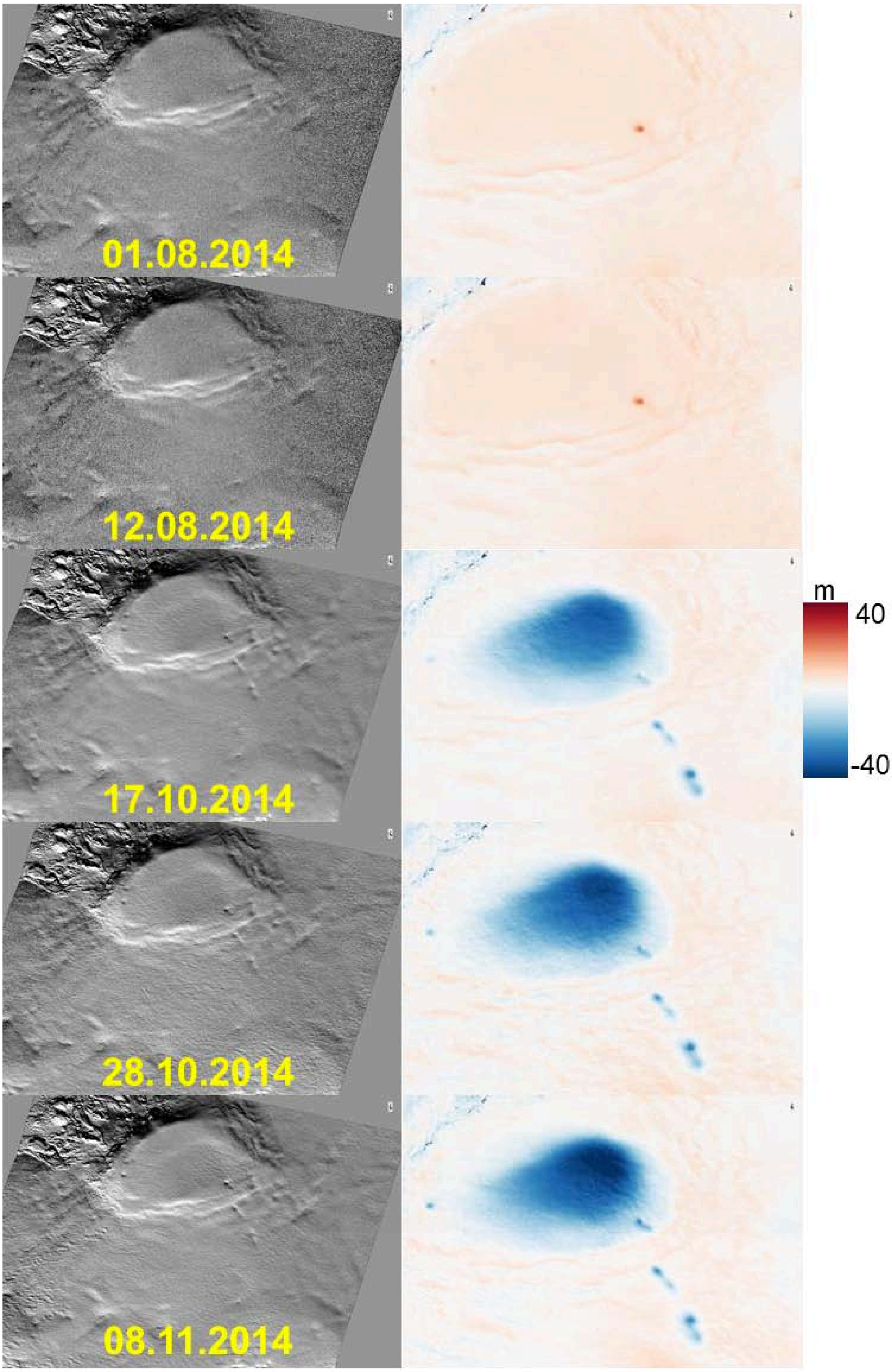


Figure 4. Series of DEMs of Bárðarbunga durin 1 August to 8 November 2014. Details of the surface changes caused by the subsidence of the Bárðarbunga caldera, left: shaded RawDEM, right difference of the RawDEM to the TanDEM-X final DEM.

6 Skaftárkatlar subglacial geothermal areas, NW-Vatnajökull

Background

The two Skaftákatlar (Skaftá cauldrons) drain in jökulhlaups into river Skaftá (Figure 5) (Björnsson, 1977). They are not connected and each follows its own pattern of water accumulation and drainage. The Eastern cauldron is the larger of the two and more powerful. As a surface feature it has a diameter of about 3 km and is roughly circular in shape with a depth in the range 50-150 m. On average 0.2-0.3 km^3 of water are drained from the cauldron in each jökulhlaup. In the period 1955-2010 jökulhlaups occurred on average once every 2.3 years (Zóphóníasson, 2002, Atladóttir et al., 2013). The period 2010-2015 was unusual, as just over five years passed after the 2010

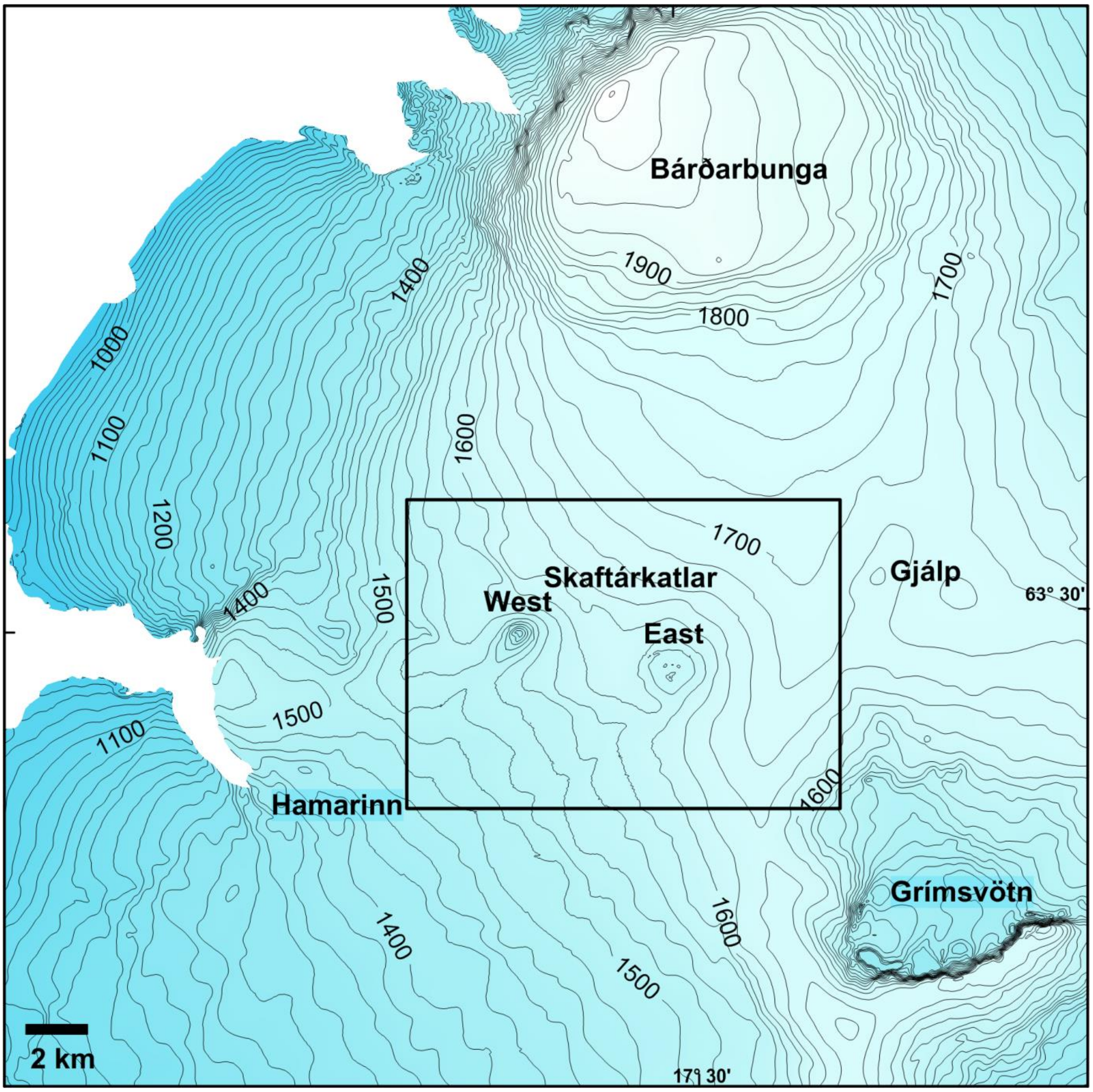


Figure 5. The northwestern part of Vatnajökull with the two Skaftárkatlar geothermal areas, located between the central volcanoes Grímsvötn, Bárðarbunga and Hamarinn. Surface contours from Lidar surveys in 2010 and 2011 (Jóhannesson et al., 2013). The frame delineates the area in Figure 6.

jökulhlaup until the cauldron was drained again at the beginning of October 2015. This jökuhlaup was also unusually large,with a volume of 0.4 km^3. A full list of known jökuhlaups with best estimates of volumes drained from the two cauldrons since 1955 is given in Table 1 (p. 12) in Aradóttir et al. (2013).

The western cauldron is slightly smaller and elliptical in shape, being slightly elongated SW-NE (Figure 5). Its depth is similar to that of the eastern one and the drainage and water accumulation cycle is similar. The jökulhlaups from the western cauldron are slightly more frequent with the average recurrence period after 1970 being just over two years (Atladóttir et al., 2013). The jökulhlaups are also smaller, on average draining 0.1-0.15 km^3 of water (Atladóttir et al., 2013).

The power of the geothermal areas has been estimated from calorimetry, using the volume of water drained and subtracting the expected contribution from surface ablation. Björnsson (2003) obtained ***800 MW*** as the geothermal power of the eastern cauldron. Using volume of meltwater drained from the western cauldron in Atladóttir et al. (2013) and following Björnsson (2003) in assuming that surface ablation accounts for 25% of the total, we obtain a mean value of ***400-500 MW*** for the western cauldron. This is an average for the period 1970 to 2010. This is not significantly different from the value of 550 MW obtained by Einarsson (2009) for the decade 1996-2006.

Observations 2000-2015

On Figures 6 and 7 the profile observations done in the period June 2000 to October 2015 are displayed. There are 20 profiles in total. Four of these are over-snow traverses on snowmobiles using differential GPS (2000-06-16, 2002-06-03, accuracy ±2 m) and kinematic GPS (2013-06-07, 2014-06-06, accuracy ±0.2 m). The remaining 16 are obtained from the aircraft TF-FMS using the radar altimeter. Note that not all profiles are along exactly the same track, comparison with the map (Figure 6) shows that the black, brown and blue profiles (2000-06-15, 2000-11-04, 2002-06-03) do not fit well with the others and the apparent differences seen on these dates in the western cauldron are due to profile location, not ice surface changes.

The profiles taken soon before or after draining of the cauldrons are shown in Figure 8. The profiles show that subsidence in the western cauldron can be 70-100 m and that the width of the subglacial lake is about 1 km (Figure 8 and 9). For the eastern cauldron the width is 2-3 km and the subsidence is about or exceeds 100 m in the western part of the cauldron. The profiles surveyed before and after the 2015 jökulhlaup show that the subglacial water body is considerably more extensive than in previous jökulhlaups for which similar data exist (2002, 2003 and 2006).

The apparent forms, thicknesses and widths of the subglacial water bodies in the two cauldrons before jökulhlaups are shown in Figure 9. It is assumed that bedrock undulations under the cauldrons are minor. This assumption is not well constrained but should not be of major importance when considering the overall shape of these water bodies. It is further assumed that ice flow is dominated by the vertical subsidence during and shortly after the jökulhlaup. This is expected to hold for horizontal flow in the 4-29 days after a jökulhlaup for the eastern cauldron. For the western cauldron the time between jökulhlaup and profiling is sometimes longer and the assumption may be less well founded than for the eastern one. Details of the shapes of these water bodies will have to be studied in more details with radio-echo soundings.

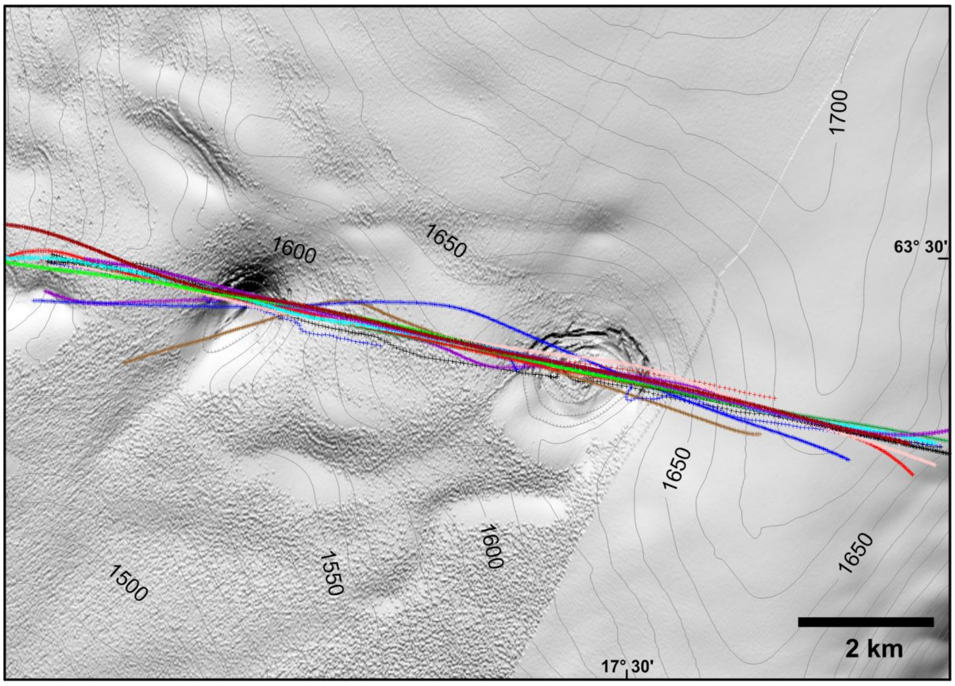


Figure 6. The two Skaftá cauldrons, the west to left, the east to the right. The lines mark flight paths over the two cauldrons with TF-FMS. The surface is from Lidar surveys in 2010 (smooth areas) and 2011 (rough surface due to differential surface ablation resulting from tephra cover after the May 2011 Grímsvötn eruption).

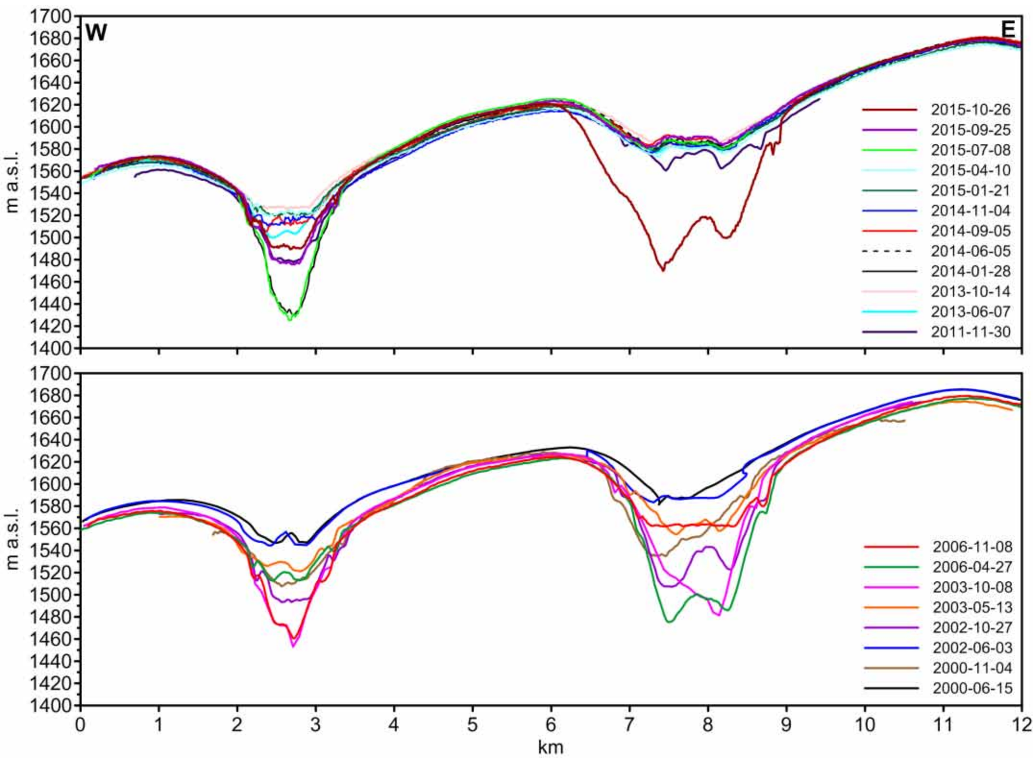


Figure 7. Surface profiles over the western and eastern Skaftárketill. Upper panel: 2011-2015, lower panel 2000-2006.

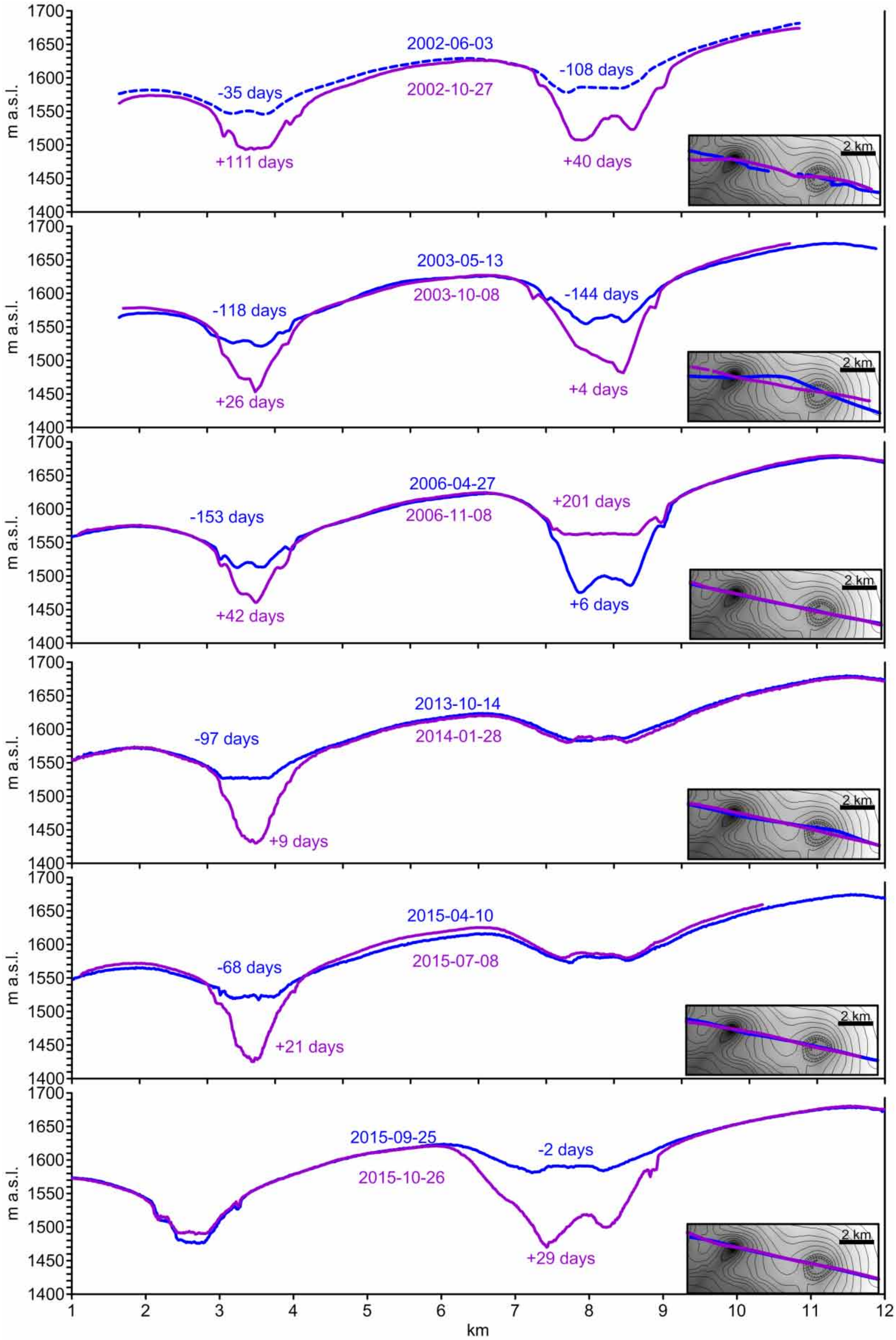


Figure 8. Ice surface profiles from TF-FMS surveys before and after jökulhlaups in 2003, 2006, 2014 and 2015. Time since (positive numbers) or until a jökulhlaup occured (negative numbers) is displayed. Note that the cauldrons behave independently and do not drain at the same time.

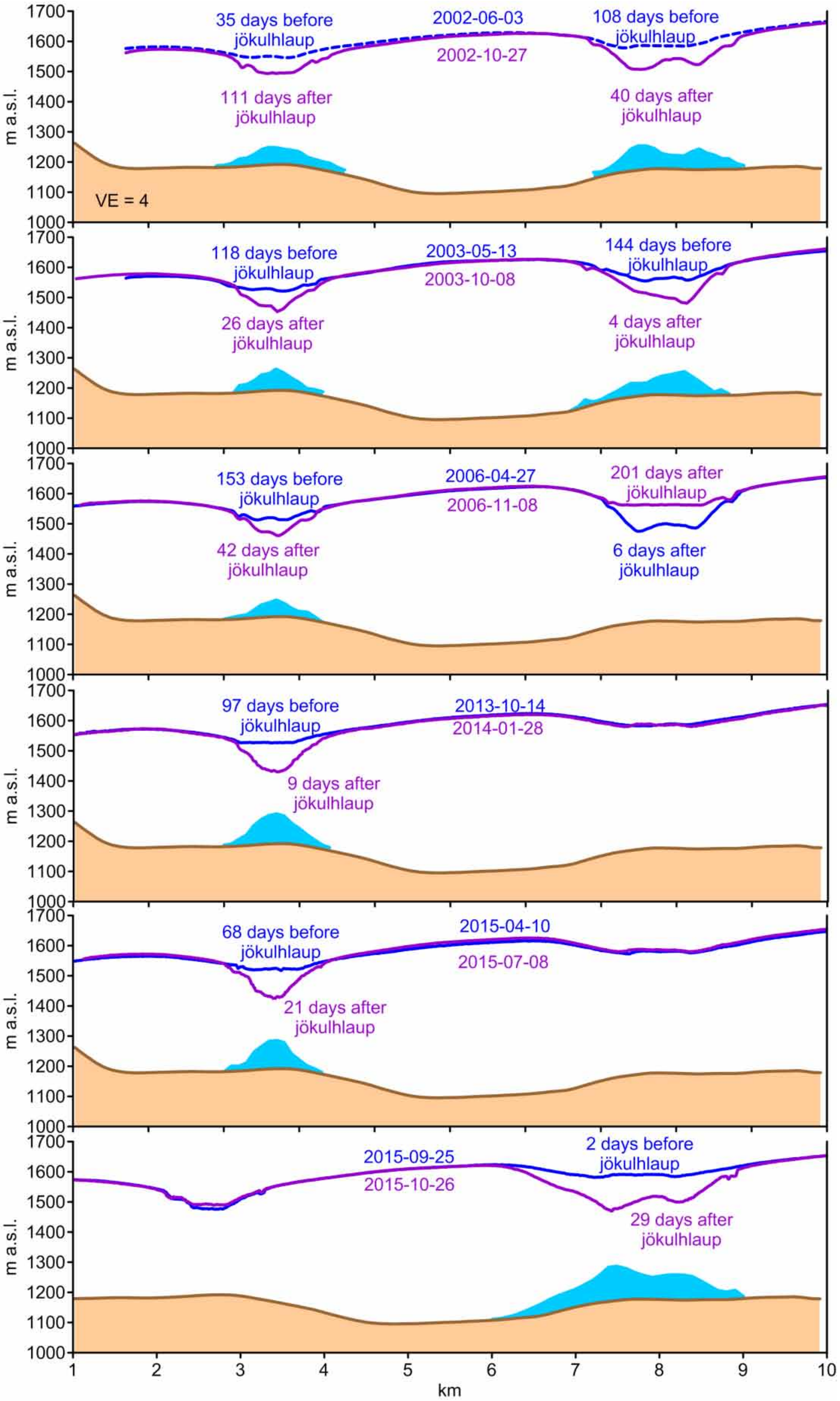


Figure 9. Form and extent of water body beneath the two Skaftárkatlar geothermal cauldrons , obtained by assuming that ice movement is predominantly vertical during subsidence when the cauldrons drain. The water body beneath the eastern cauldron expanded considerably in 2010-2015, as found be comparing it in 2002 and 2003 profiles (top) with the one from 2015 (bottom).

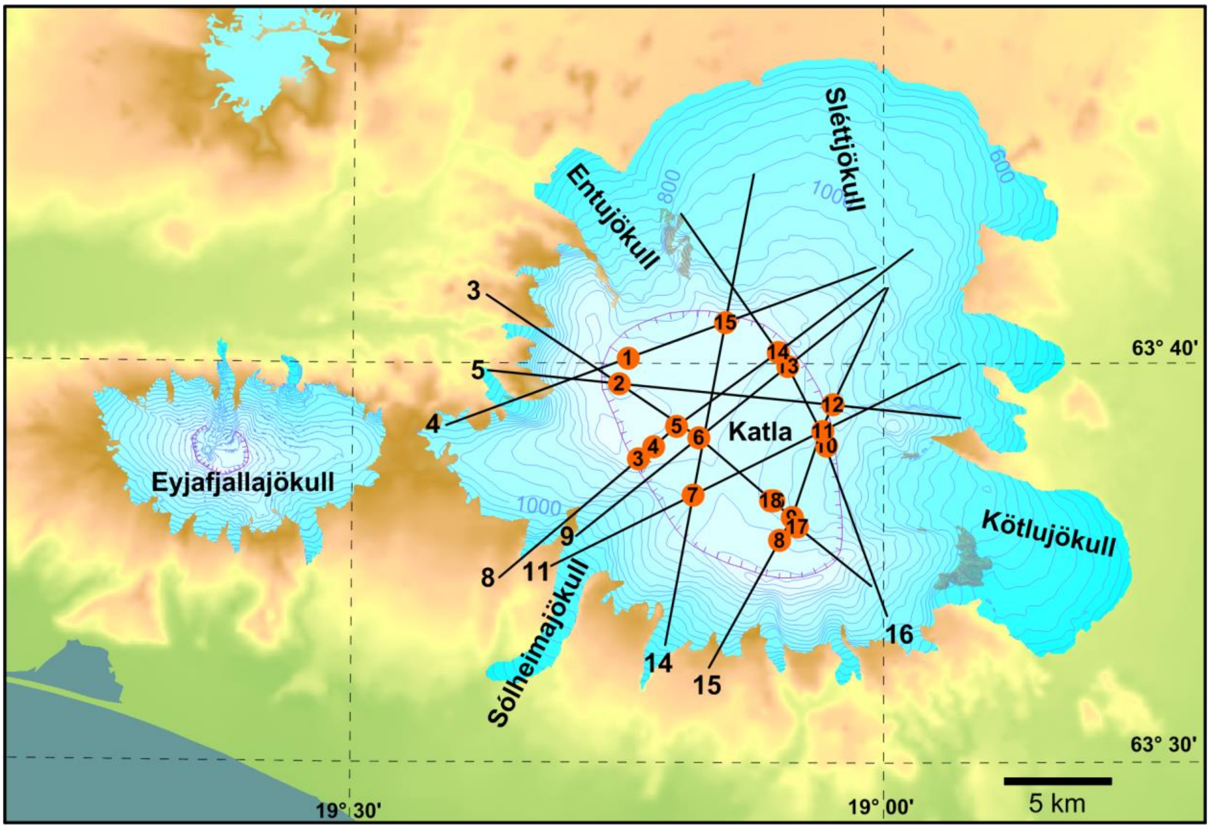


Figure 10. Survey lines accross Katla, used for aircraft altimeter surveys 1999-2015.

The profiling suggests that the water body in the western cauldron has similar form from one jökulhlaup to the next, a width of about 1 km and thickness of 70-100 m. For the eastern cauldron the body is broadly similar between jökulhlaups. It is about 2 km wide in 2002 and 2003. However, this may be a slight underestimate since 108 days passed between profiling and the jökulhlaup in 2002 and 144 days in 2003. For 2015, the water body seems to have grown considerably relative to previous years, reaching a width of 3 km. This widening concurs with observations on the surface, where the distance across the cauldron between the concentric crevasses marking the subsidence increased also. These data are now being used for more detailed analyses of temporal changes in the cauldrons.

7 Cauldrons in Katla

Geothermal changes in the Katla caldera, as manifested in depth and width of ice cauldrons has been ongoing since 1999 using the radar altimeter profiling. These surveys form a part of the network used to monitor Katla (Gudmundsson et al., 2007). There are 17 semi-permanent cauldrons known within and by the margins of the Katla caldera (Figure 10), numbered from 1 to 17 and a cauldron numbered 18 on map was observed in July 2011. These cauldrons are regularly monitored with about two flights per year along nine flight lines. This frequency is sufficient to detect gradual changes in cauldrons that do not accumulate water to a considerable extent. More rapid changes would need more frequent surveying. The results of the profiling in relation to geothermal variations are summarised in Figure 11, where all the cauldrons are shown as dots, with colouring indicating whether they are deepening (geothermal activity increasing) or getting shallower (usually indicating decreased geothermal activity) or show insignificant changes. The Figure shows that an increase in geothermal activity took place in 1999, a decline from that high occurred in 2000 while in 2001-2003 some heating occurs. This heating reaches a maximum in 2004-2006. A decline in activity is registered in 2009-2010 while a sharp increase in the southern part occurred in 2011. That increase has stopped and after some decline in 2012 the geothermal activity within caldera is mostly stable in 2013-2015.

The peaks observed in 1999, 2003-2006 and 2011 correlate with increases in seismicity and apparent inflation of the caldera (Sturkell et al., 2008, Gudmundsson et al., 2007). Both the increase in 1999 and 2011 where accompanied with sudden, unexpected jökulhlaups (Sigurðsson et al., 1999; Galeczka et al. 2014).

In Figures 12 to 25 all profile data obtained for the nine Katla survey lines in 1999-2015 are displayed. A detailed interpretation is not presented here but three examples are given below:

1. The evolution of cauldron 7 (seen on survey lines 11 and 14) is notable as it declines markedly after 1999. It was the source of the sudden flood that took place in July 1999. After this event the cauldron was 50 m deep. Subsequently cauldron 7 became shallower, declining to about 25 m depth after a few years.
2. Cauldron 11 (lines 11, 15 and 16) has gone through periods of marked deepening and shallowing. It has also shown signs of periodic drainage, manifested in marked deepening between spring and autumn.
3. The third and final example of notable events in this period is the behaviour of cauldron 16 (line 3). It was quite indistinct in the first years of surveying, but soon began to show signs of accumulation in winter and drainage in summer. It was measured on 6 July 2011 and had by that time risen by 5-10 meters relative to the previous year. This increase was followed by the sudden drainage and deepening by tens of meters on 9 July 2011. During the resulting jökulhlaup the bridge on highway 1 over river Múlakvísl was destroyed. Since 2011 the cauldron has declined again.

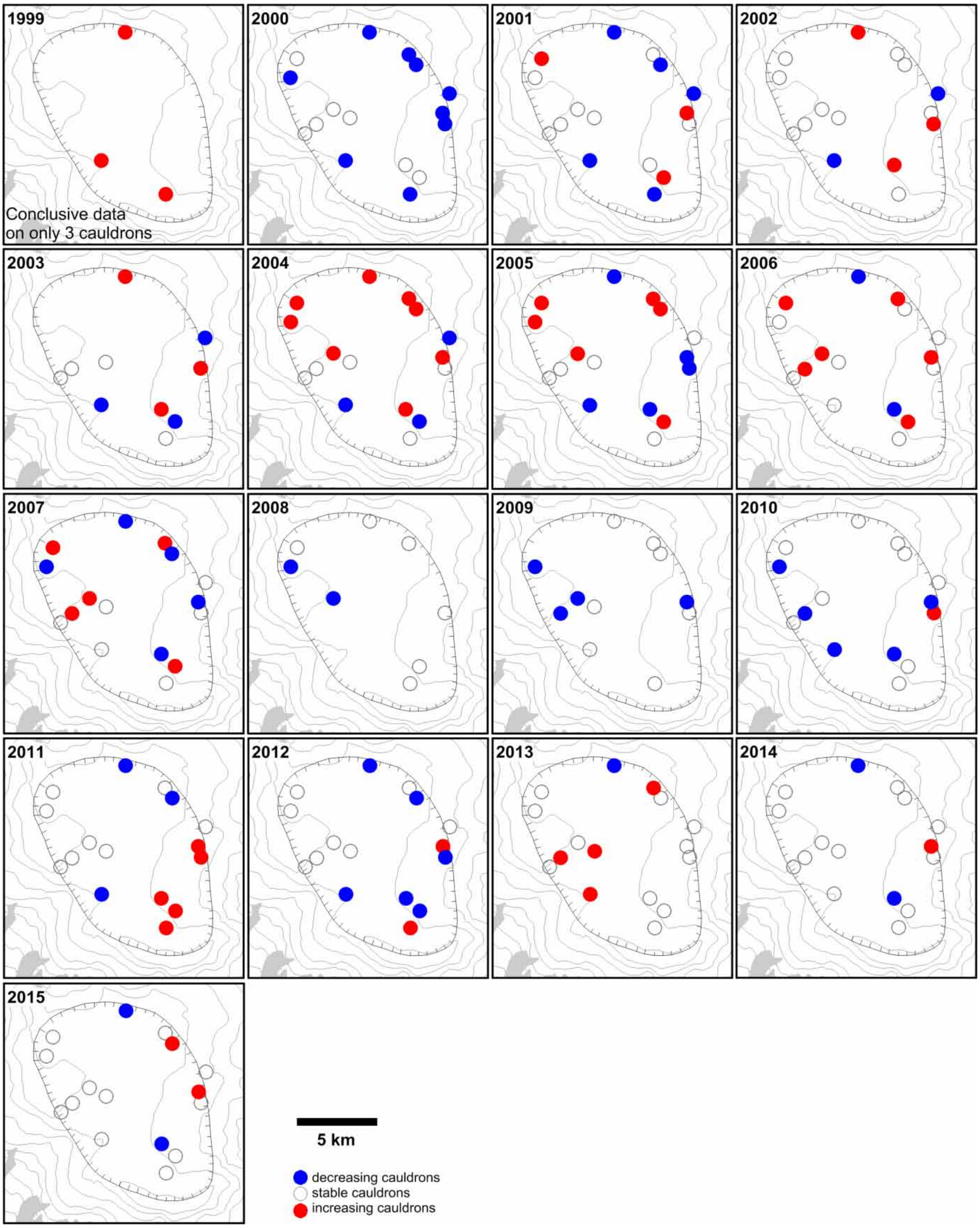


Figure 11. Variations in geothermal activity in the Katla caldera 1999-2015, as registered in ice cauldron depth. A cauldron in considerd as increasing if its depth increases by more than 5 m in period of 6-12 months, decreasing if it depth decreases by 5 m, and stable if depth changes are less than 5 m.

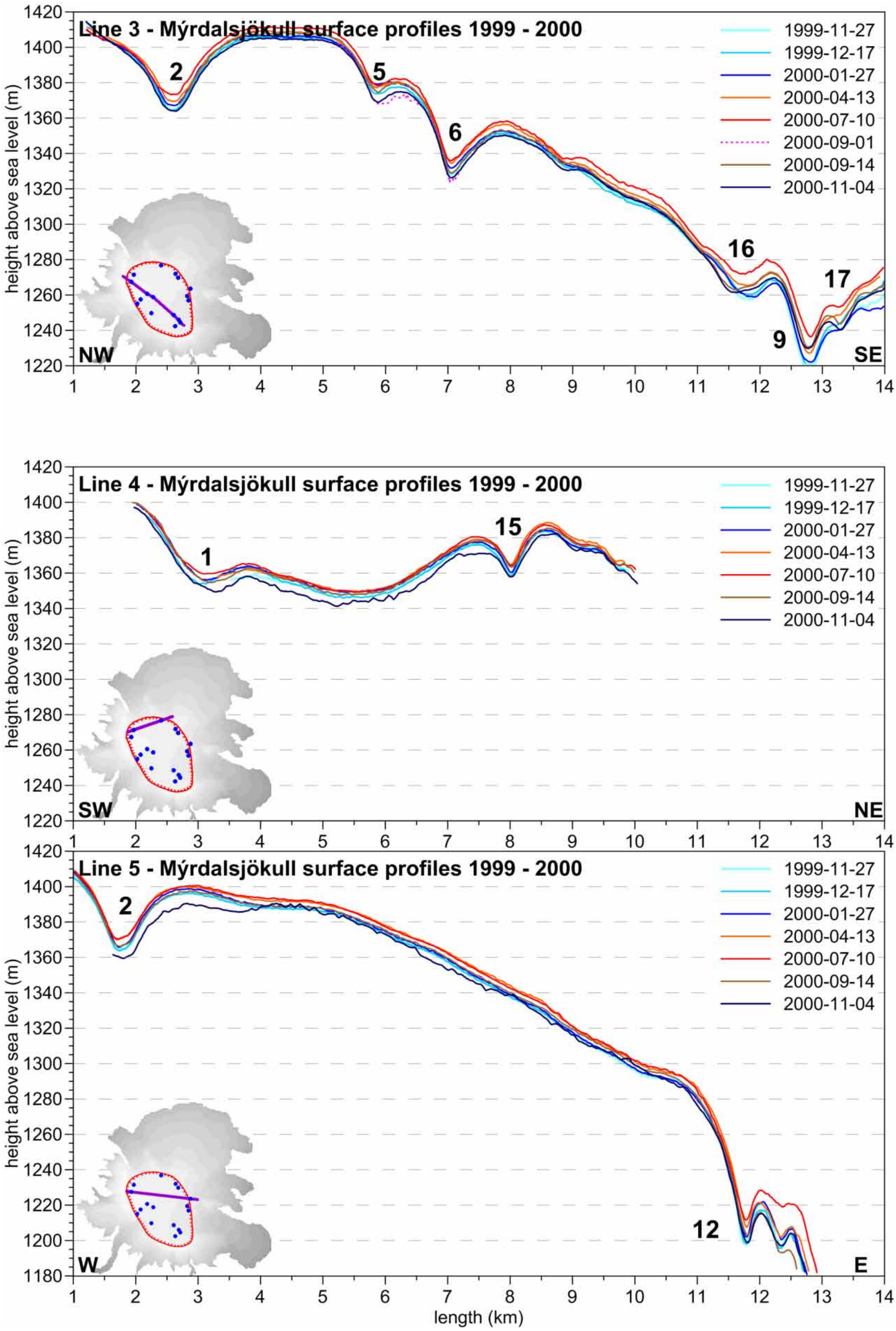


Figure 12. Katla: Survey lines 3, 4 and 5 in 1999-2000. The Survey line 3 includes cauldrons 2, 5, 6, 16, 9 and 17 (numbers on profile), Line 4 cauldrons 1 and 15 and Line 5 cauldrons 2 and 12.

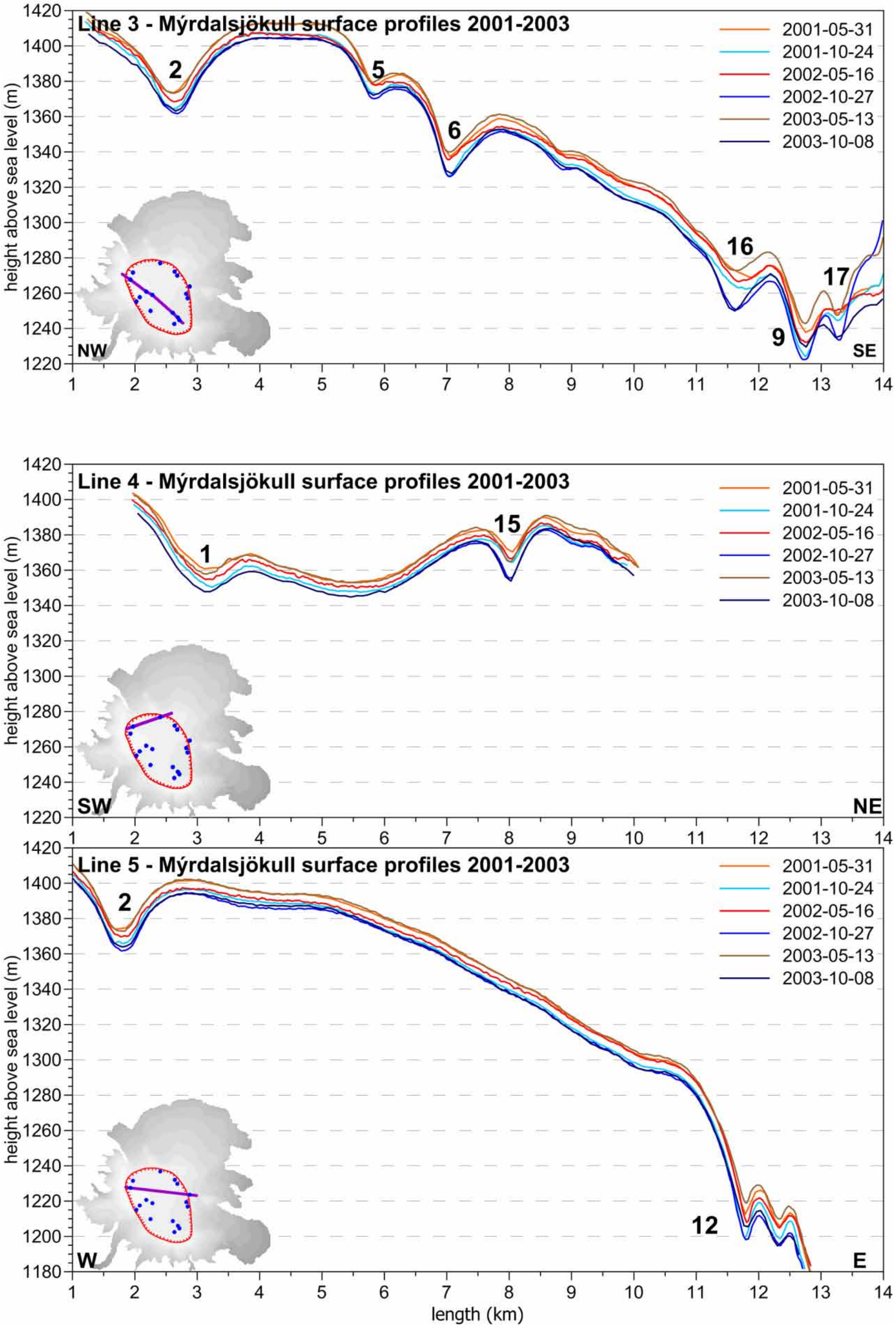


Figure 13. Katla: Survey lines 3, 4 and 5 in 2001-2003.

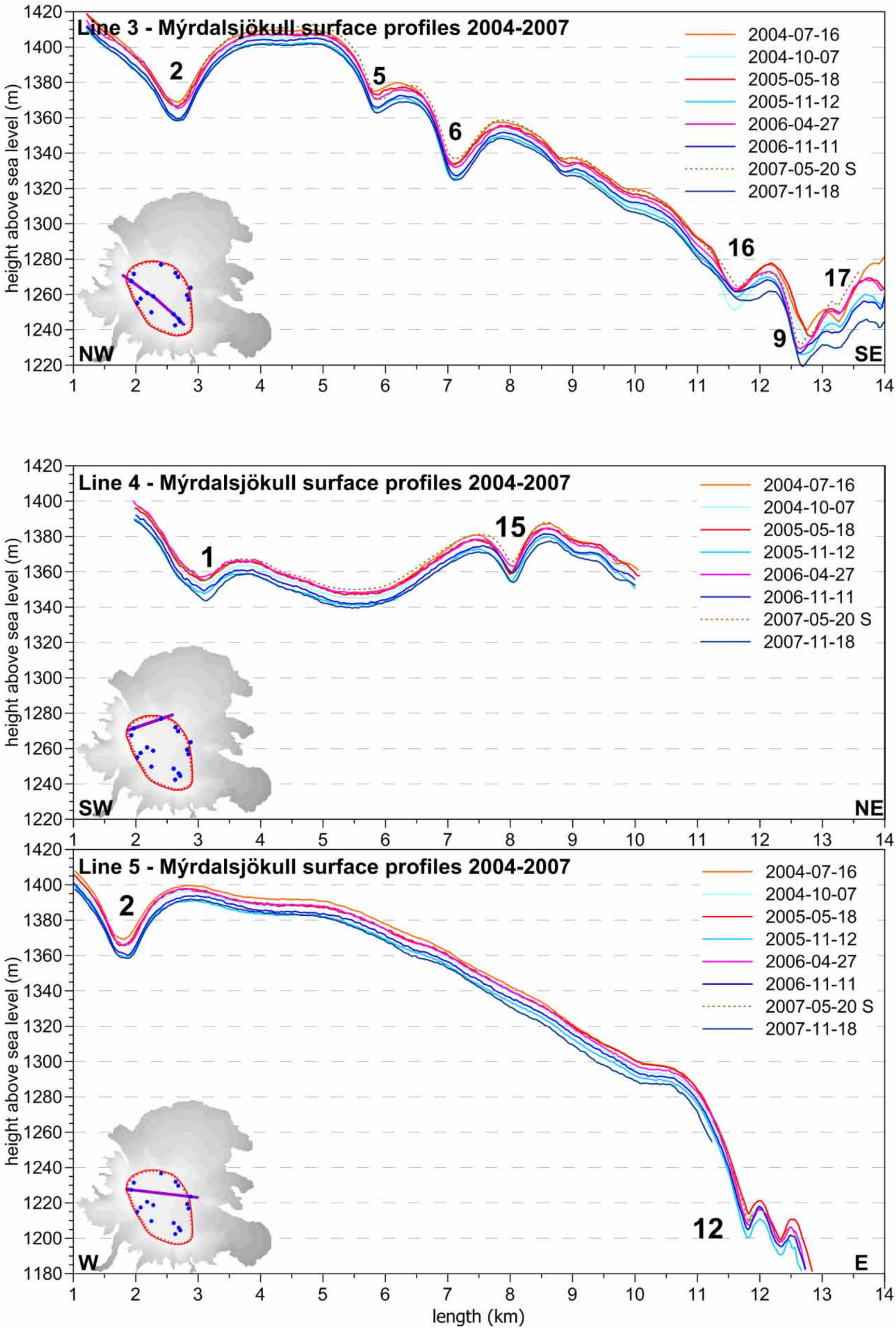


Figure 14. Katla: Survey lines 3, 4 and 5 in 2004-2007. No survey in 2008.

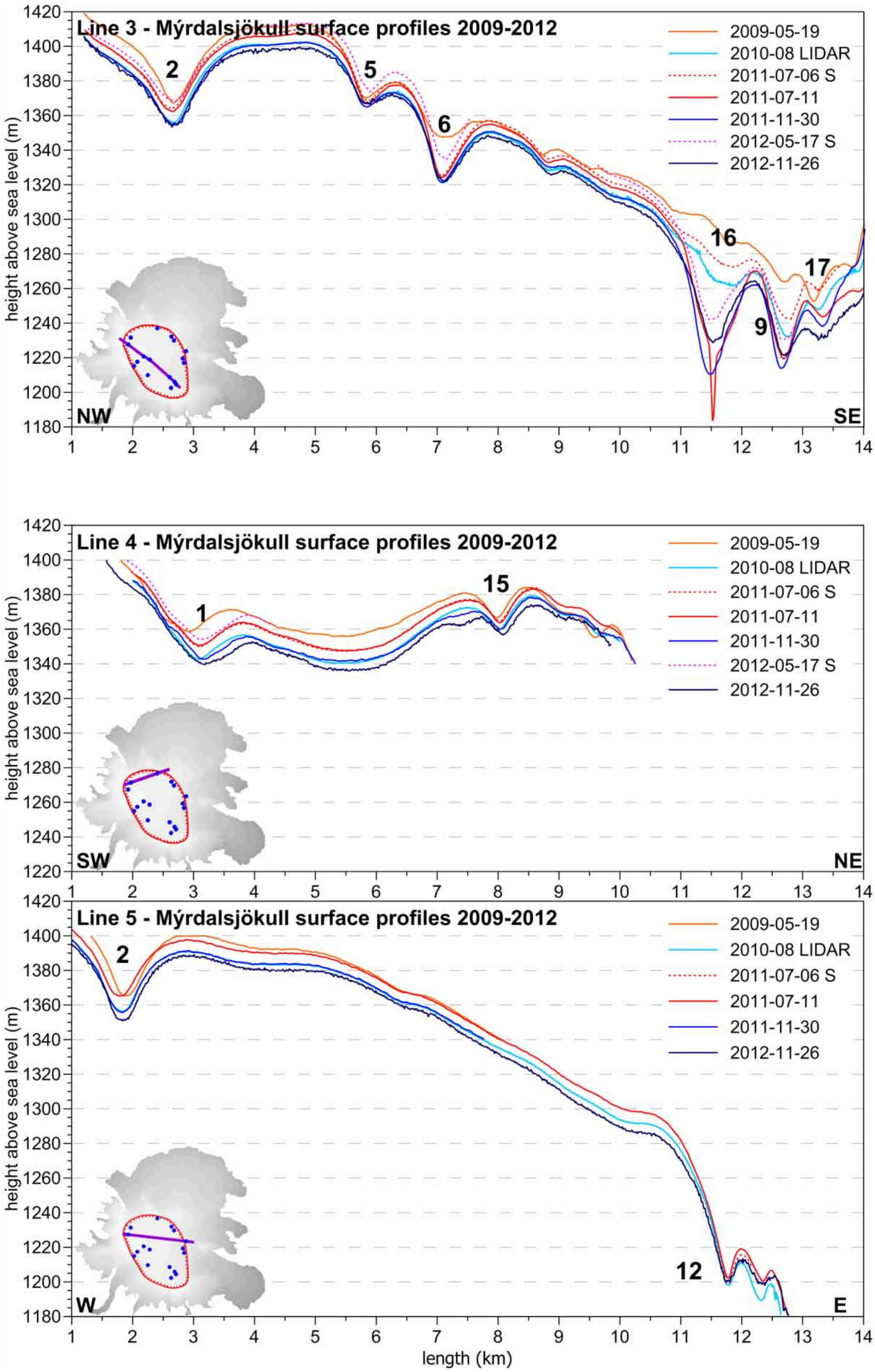


Figure 15. Katla: Survey lines 3, 4 and 5 in 2009-2012.

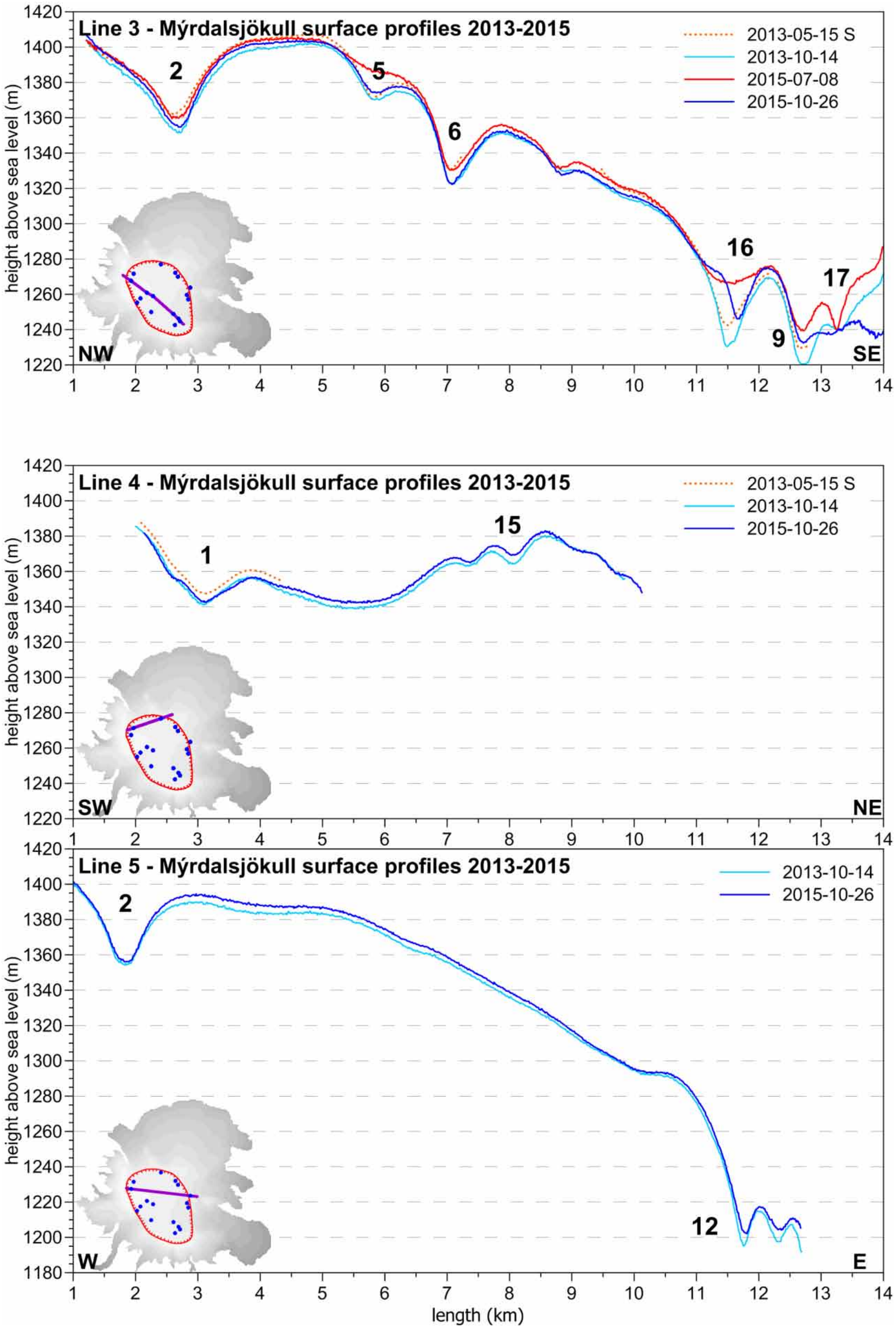
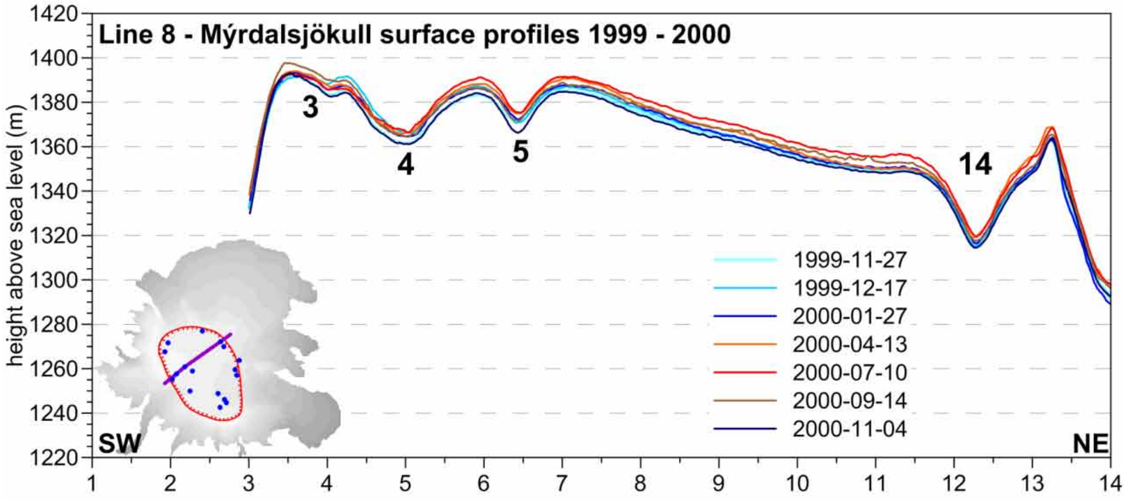
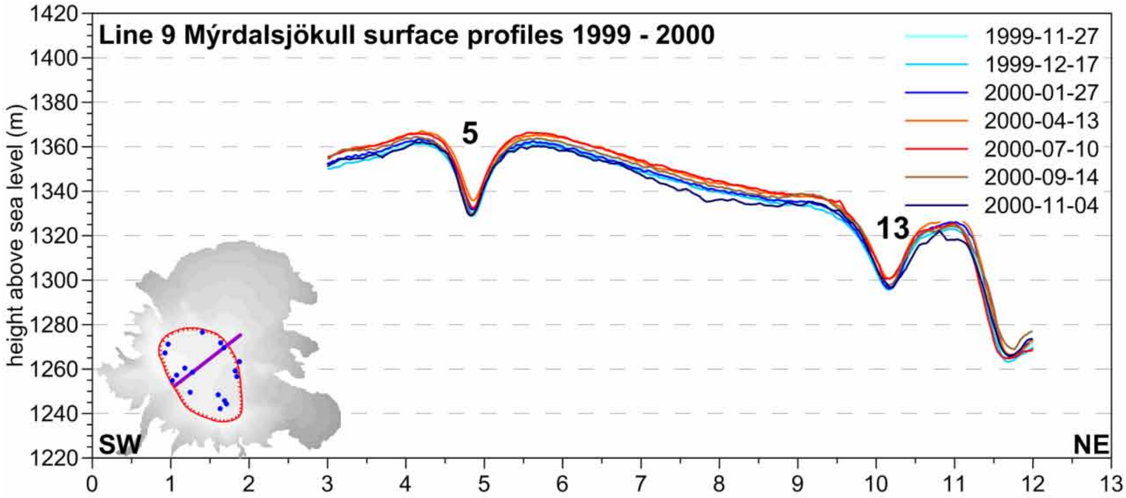


Figure 16. Katla: Survey lines 3, 4 and 5 in 2013-2015.





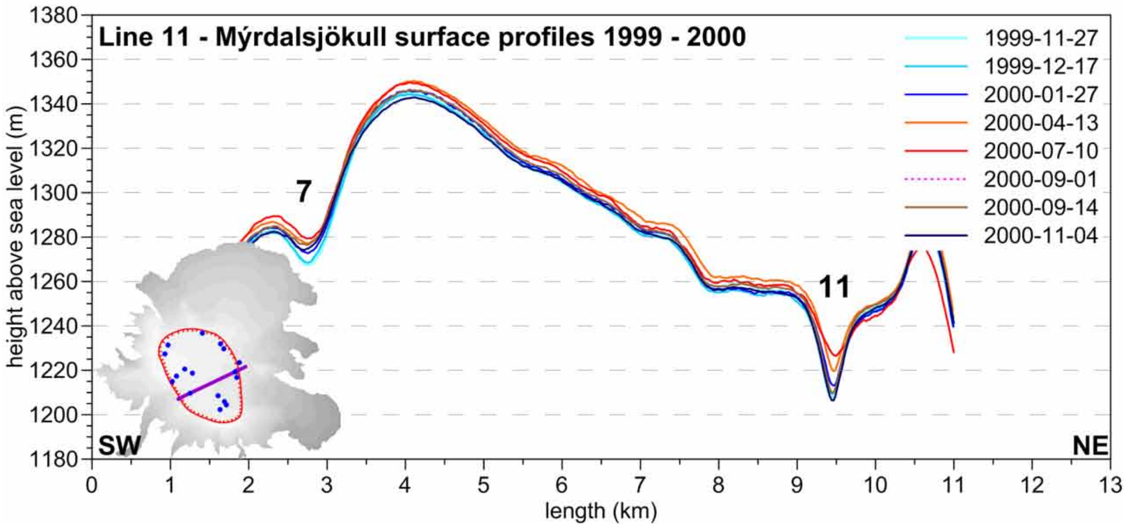


Figure 17. Katla: Survey lines 8, 9 and 11 in 1999-2000. Line 8 includes cauldrons 3, 4, 5 and 14. Line 9 cauldrons 5 and 13 and Line 11 cauldrons 7 and 11.

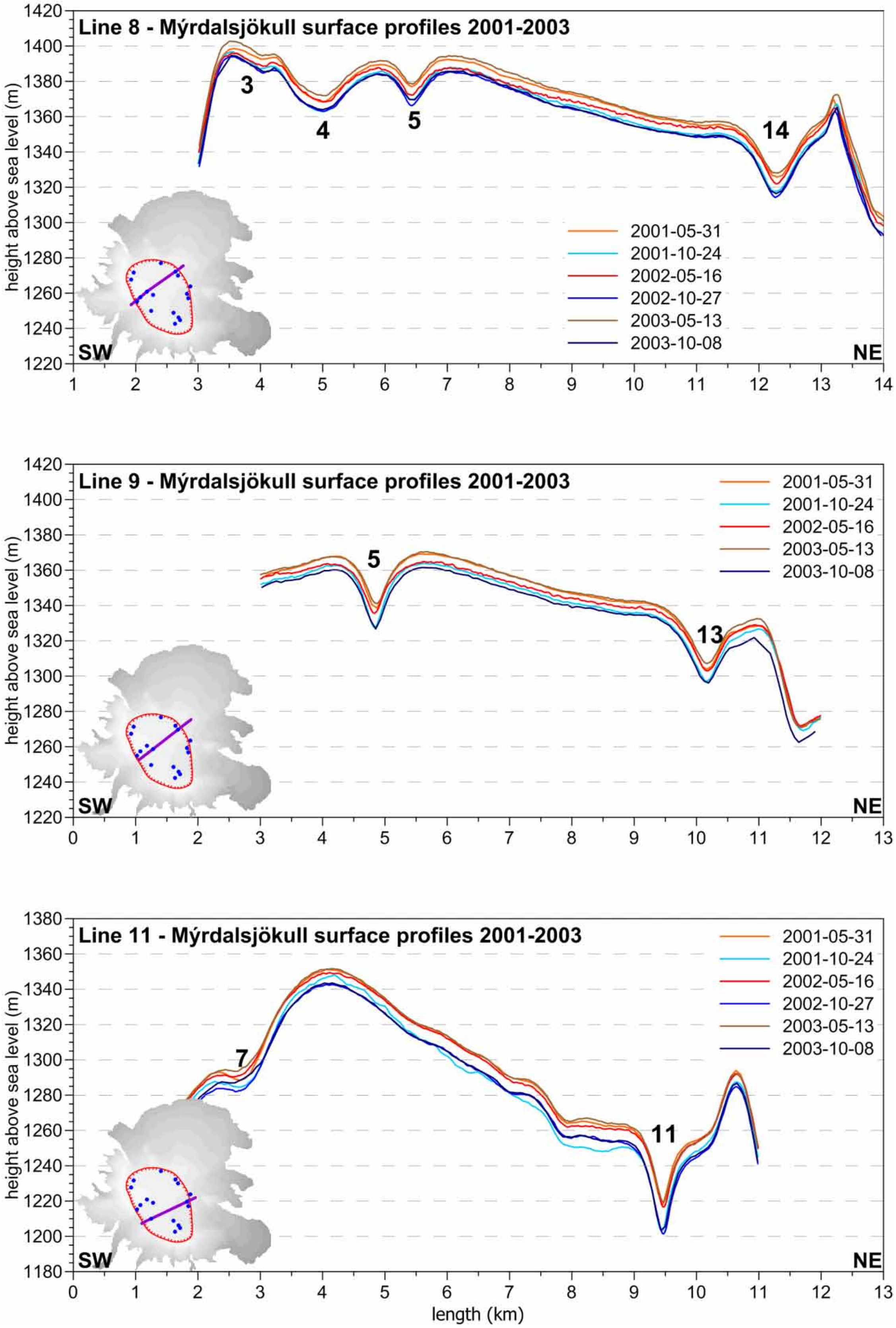


Figure 18. Katla: Survey lines 8, 9 and 11 in 2001-2003.

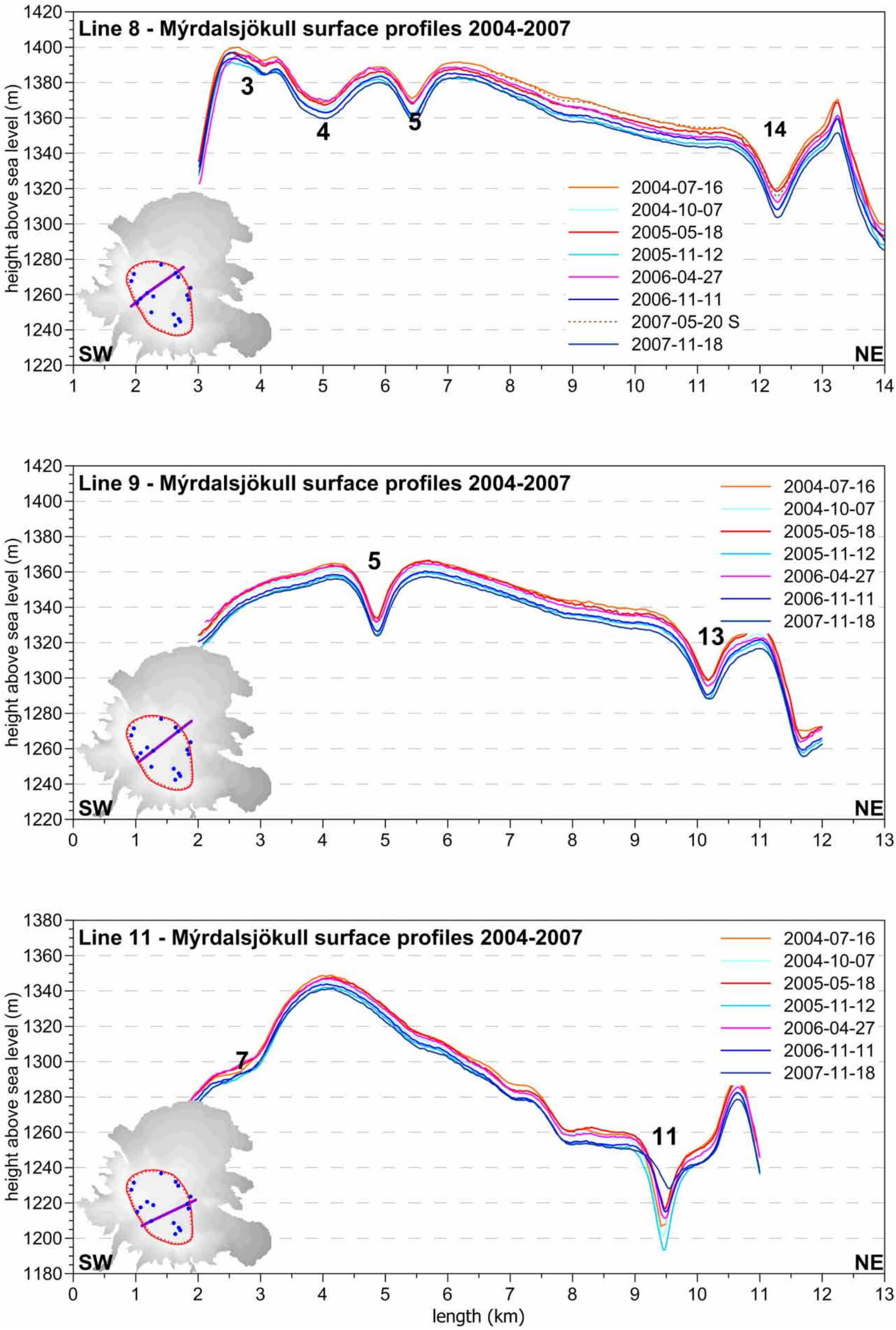


Figure 19. Katla: Survey lines 8, 9 and 11 in 2004-2007. No survey in 2008.

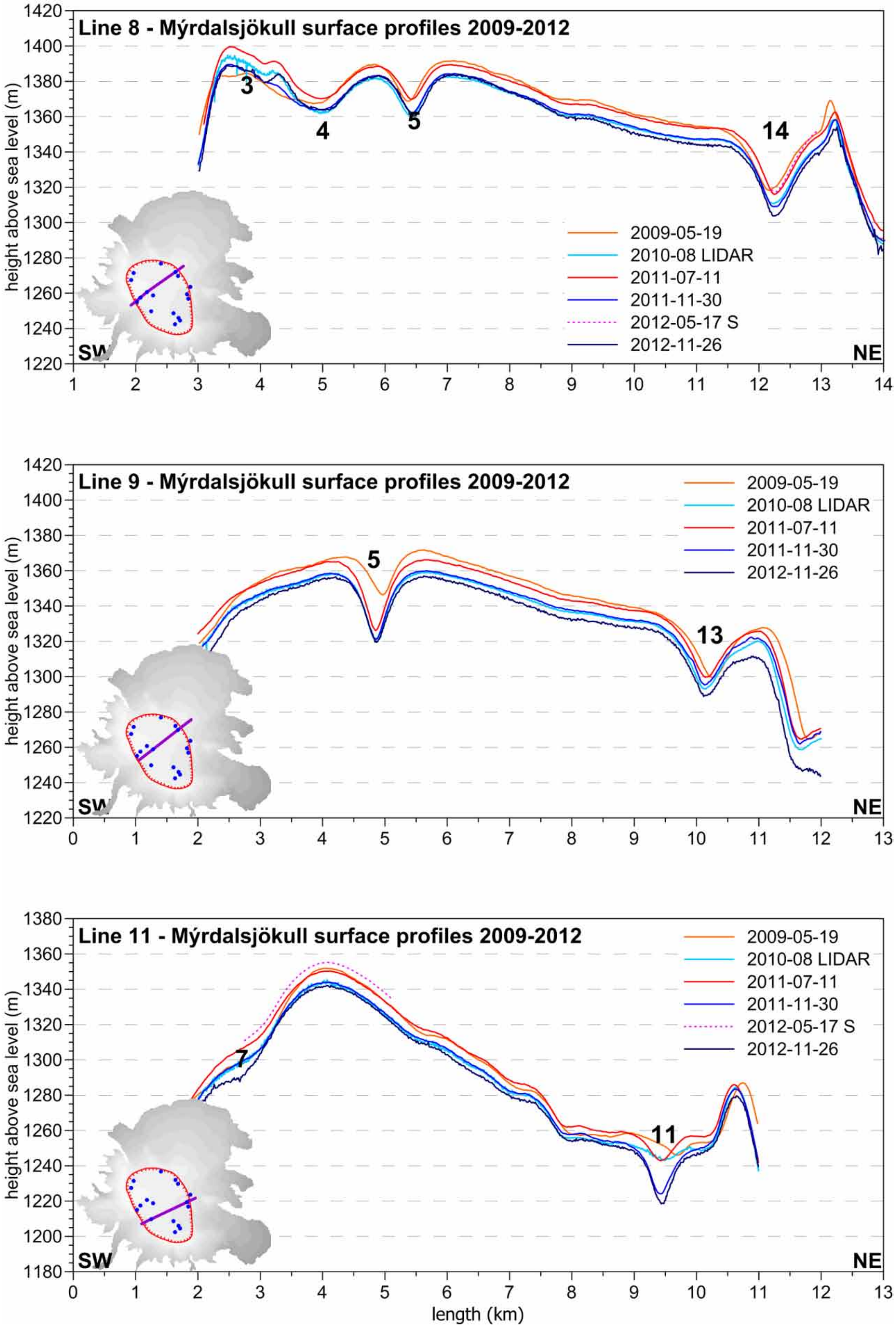


Figure 20. Katla: Survey lines 8, 9 and 11 in 2009-2012.

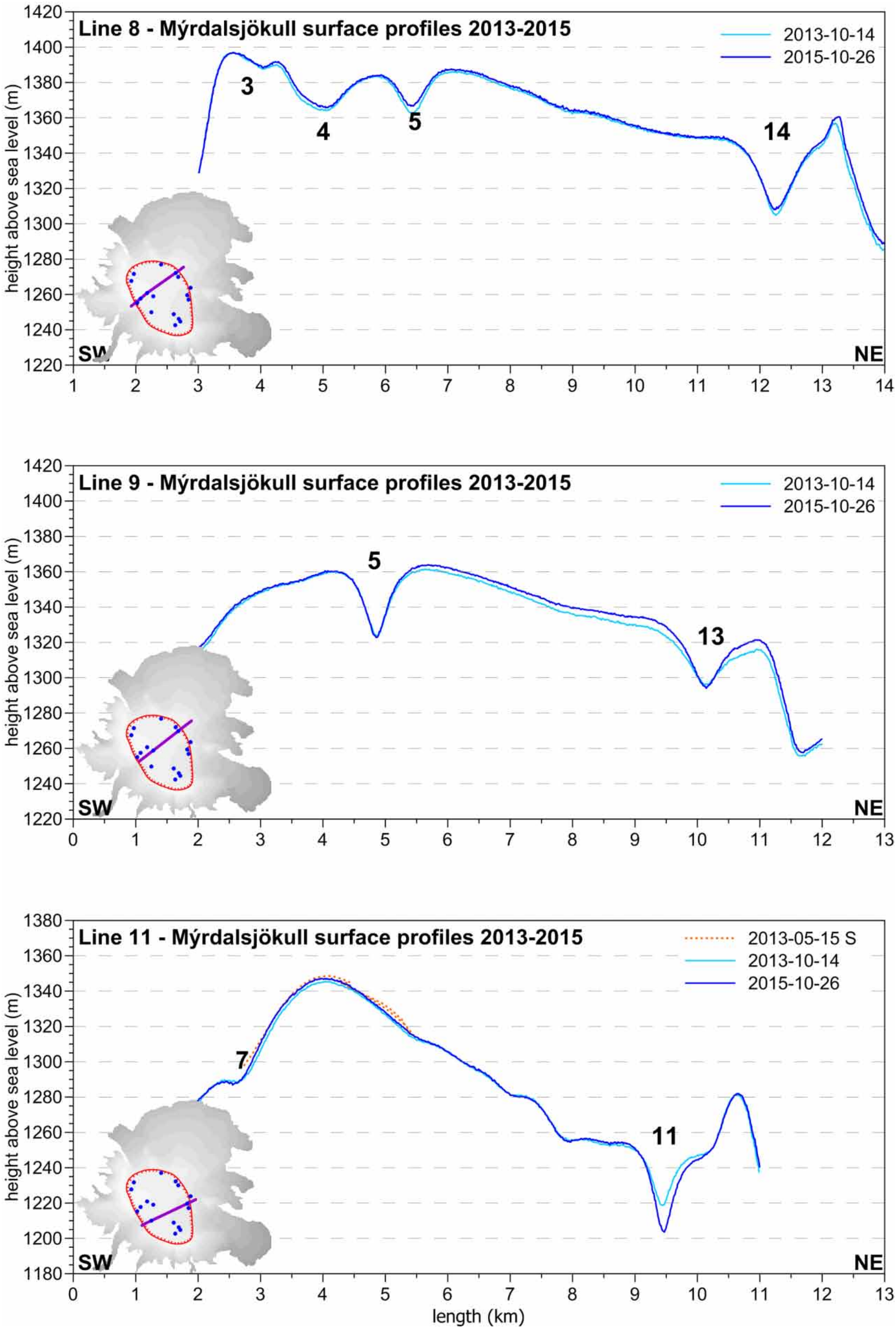


Figure 21. Katla: Survey lines 8, 9 and 11 in 2013-2015.

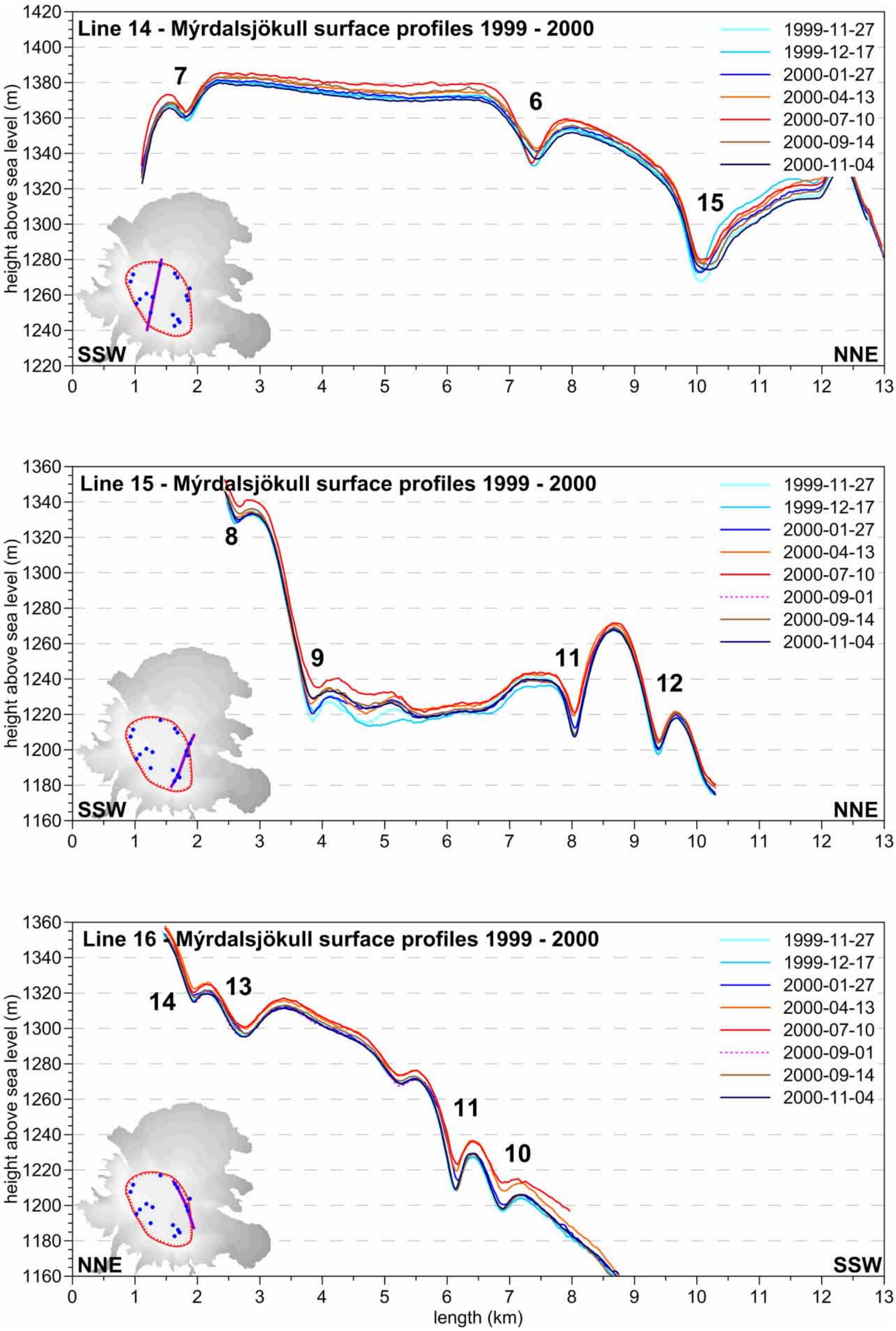


Figure 22. Katla: Survey lines 14, 15 and 16 in 1999-2000. Line 14 includes cauldrons 6, 7 and 15, Line 15 cauldrons 8, 9, 11 and 12, and Line 16 cauldrons 10, 11, 13 and 14.

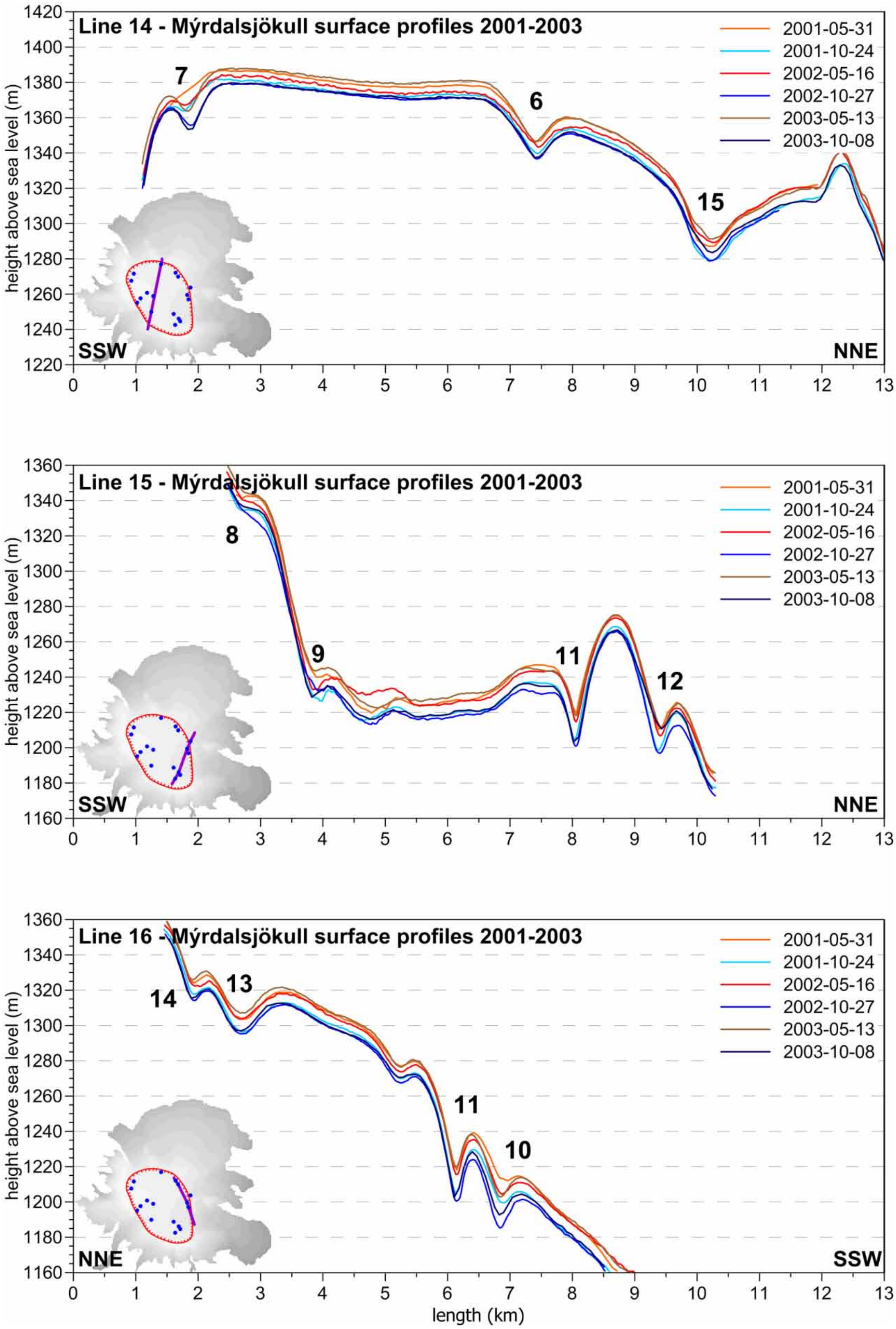


Figure 23. Katla: Survey lines 14,15 and 16 in 2001-2003.

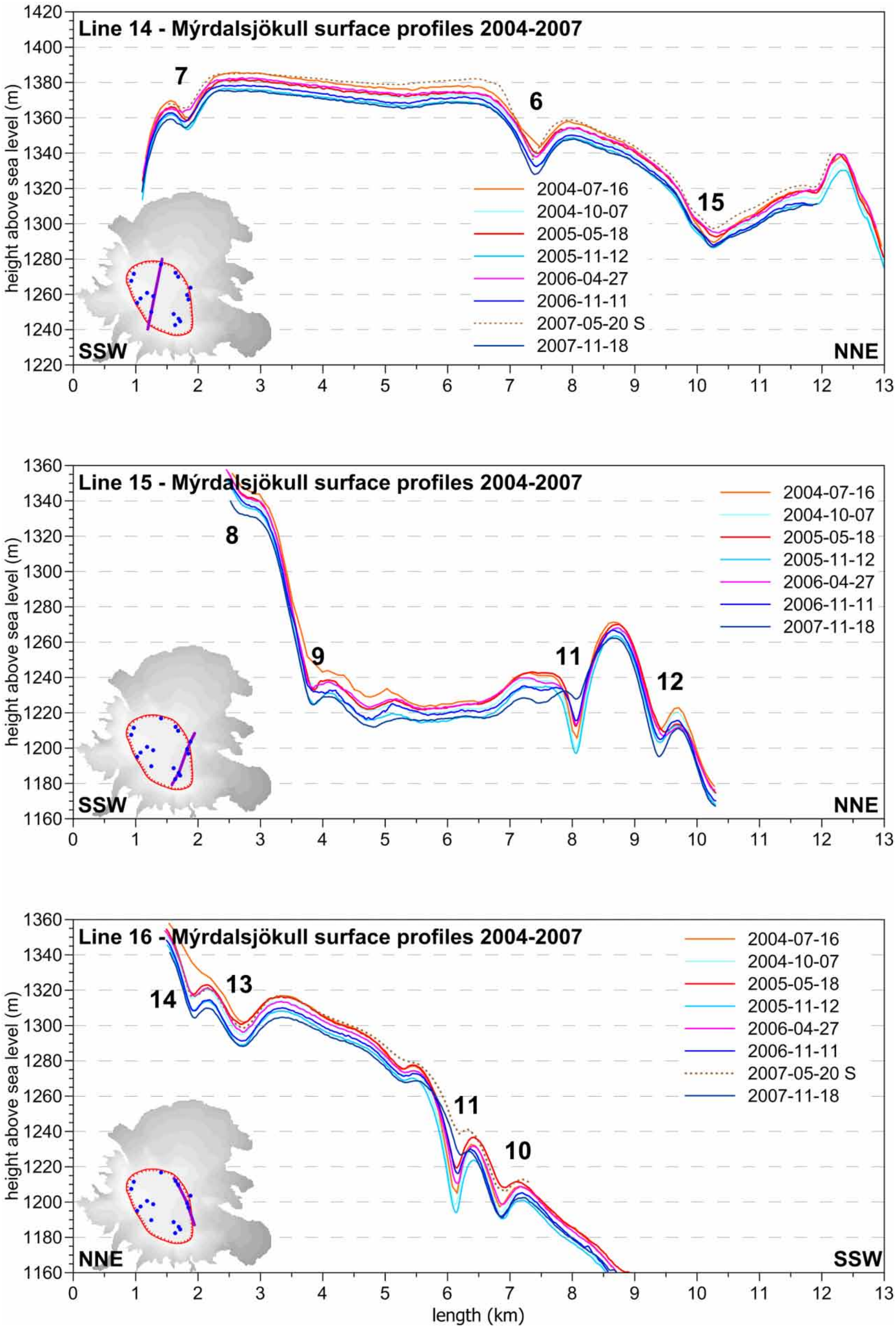


Figure 23. Katla: Survey lines 14,15 and 16 in 2004-2007. No survey in 2008.

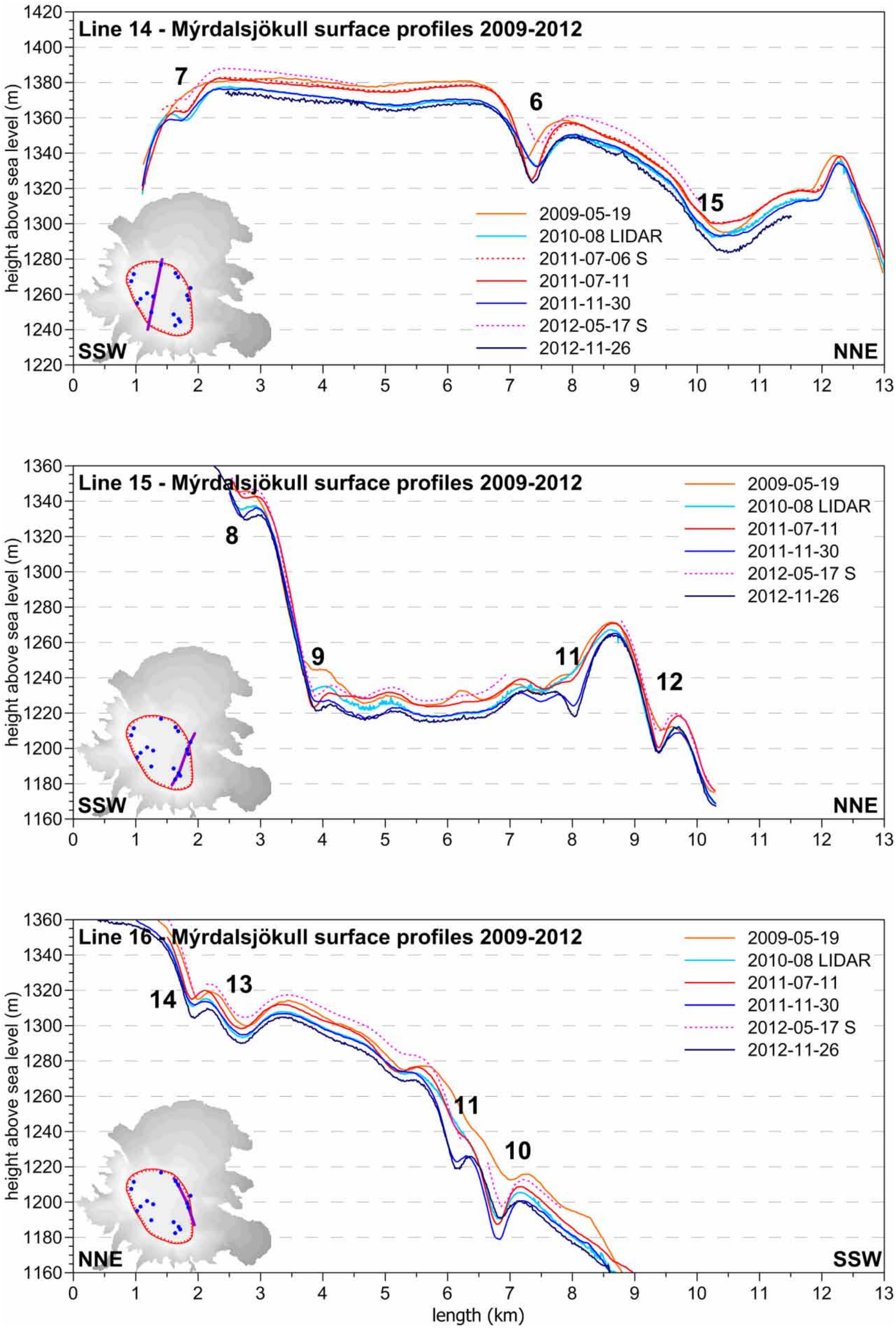


Figure 24. Katla: Survey lines 14,15 and 16 in 2009-2012.

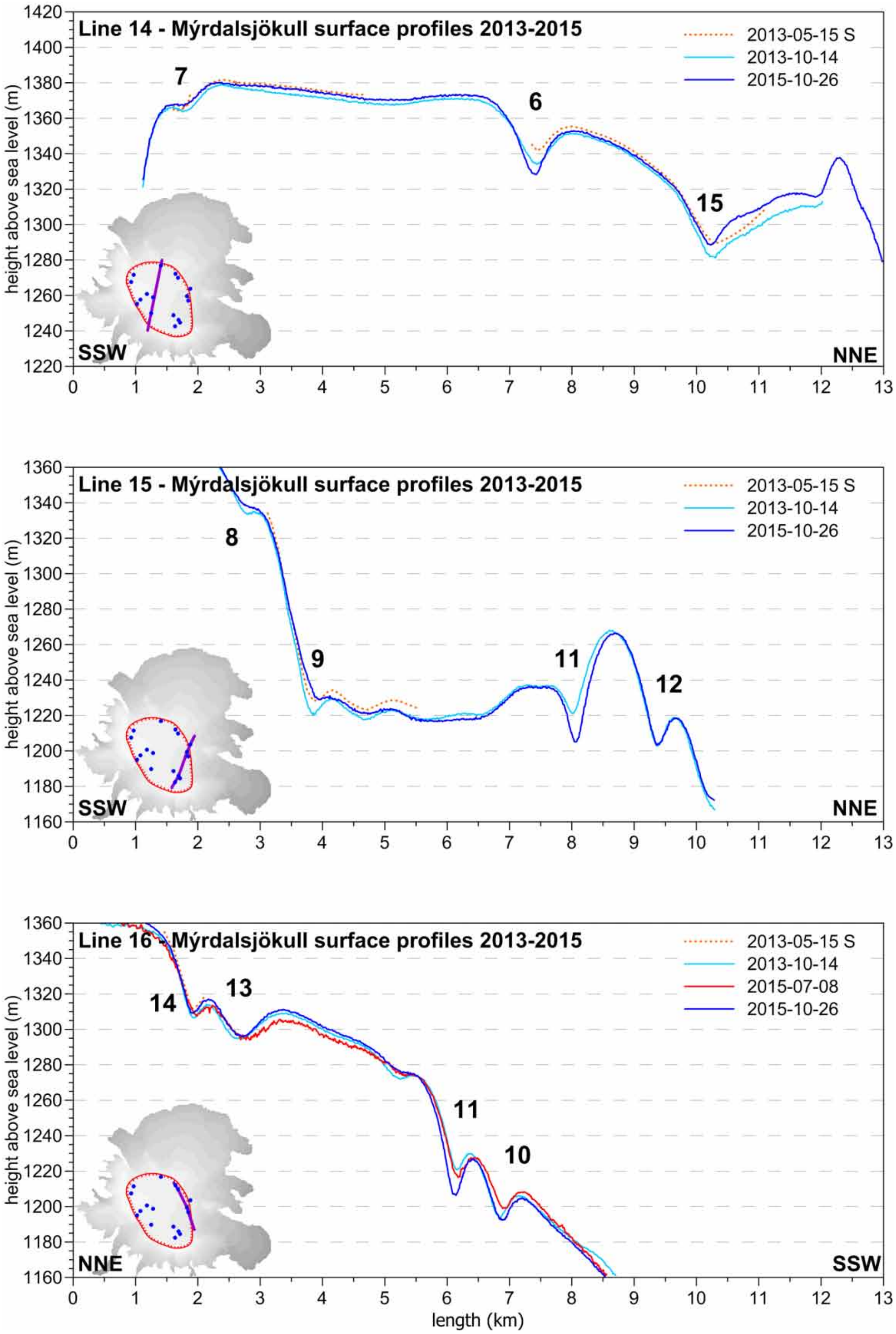


Figure 25. Katla: Survey lines 14,15 and 16 in 2013-2015.

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