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Tómas Jóhannesson
Þorsteinn Arnalds
Leah Tracy

Results of the 2D avalanche model SAMOS for Ísafjörður and Hnífsdalur

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BACKGROUND

The 2D avalanche model SAMOS, developed by the Advanced Simulation Technologies (AVL) of Graz, Austria, has been run for starting zones in the mountains above the villages Ísafjörður and Hnífsdalur, northwestern Iceland. The runs are intended to shed light on the following aspects of the avalanche hazard situation in the villages:

1. The effect of the ridge Seljalandsmúli on the flow of avalanches that are released from Seljalandshlíð to the west of the farm Seljaland.
2. The shortening of avalanche runout due to lateral spreading of avalanches. This is particularly relevant for the largely unconfined and partly convex slopes of Gleiðarhjalli below the shelf at 400-500 m a.s.l.
3. The direction of the main avalanche tongues from the starting areas that have been defined in the mountains as a part of the hazard zoning, in particular the influence of the gullies Hraunsgil, Traðargil and Búðargil on the direction of avalanches in the runout area on the northern side of Hnífsdalur.

The results of the runs will be used in the delineation of the hazard zones for the villages. Similar results have previously been used for the same purpose for the villages Bolungarvík, Neskaupstaður, Siglufjörður, Seyðisfjörður and Eskifjörður (Jóhannesson *et al.*, 2001a,b, 2002a,b). The section about the application of the model to the 1995 avalanche at Flateyri is identical to a section in the previous reports about other villages in Iceland in order to make the present report independent of the previous reports.

The SAMOS model was developed for the Austrian Avalanche and Torrent Research Institute in Innsbruck by AVL and has recently been taken into operational use in some district offices of the Austrian Foresttechnical Service in Avalanche and Torrent Control. The model is based on similar assumptions regarding avalanche dynamics as other depth integrated 2D avalanche models that are used in Switzerland and France. Friction in the dense flow part of the model is assumed to be composed of a Coulomb friction term proportional to a coefficient $\mu = \tan(\delta)$ with $\delta = 16.0°$ ($\mu = 0.287$) and a turbulent friction term which may be represented by a coefficient $\xi = 446\,\mathrm{m}^2/\mathrm{s}$ (Sampl and Zwinger, 1999). Rather than adding the two friction components as is done in the Swiss and French 2D models, the SAMOS model uses the maximum of the two friction terms and ignores the smaller term. This leads to slightly higher modelled velocities than for the Swiss and French 2D models for avalanches with similar runout. The velocities are, also, somewhat higher than corresponding velocities in the same path from the Swiss AVAL-1D model or the PCM model (Sauermoser, personal communication). The model runs are, furthermore, based on an assumed value $\rho = 200\,\mathrm{kg/m}^3$ for the density of flowing snow. The density is used to convert a given mass of snow in the starting zone to a corresponding volume or depth perpendicular to the terrain of the snow that is released at the start of the simulation.

MODELING OF AVALANCHE AT FLATEYRI ON 26.10.1995

The SAMOS model had not been used to model Icelandic avalanches before it was run in connection with hazard zoning of several Icelandic villages in the years 2000 to 2002. The model was first run for the catastrophic avalanche from Skollahvilft at Flateyri on 26 October 1995 (fig. 1) in order to check the applicability of the parameter values that are traditionally adopted for the model in Austria. The values for μ, ξ and ρ listed above were used. About 90,000 tons of snow were released from the starting zone between about 400 and 640 m a.s.l. based on measurements of the mass of the deposit of the avalanche and observations of the fracture height and density of the snow at the fracture line. The starting zone was divided into an upper and a lower area with a larger snow depth in the upper area.

The run was defined by the following input data:

Input	Value
Map area of upper starting zone ($10^3 m^2$)	58
Map area of lower starting zone ($10^3 m^2$)	52
Total map area of starting zone ($10^3 m^2$)	110
Area of upper starting zone ($10^3 m^2$)	73
Area of lower starting zone ($10^3 m^2$)	63
Total area of starting zone ($10^3 m^2$)	136
Snow depth, upper area (d_u, m, $\rho = 200\,kg/m^3$)	4.3
Snow depth, lower area (d_l, m, $\rho = 200\,kg/m^3$)	2.0
Snow depth, average (m)	3.25
Mass ($10^3 t$)	89
Volume ($10^3 m^3$, $\rho = 200\,kg/m^3$)	440
Volume ($10^3 m^3$, $\rho = 350\,kg/m^3$)	220
Volume ($10^3 m^3$, $\rho = 420\,kg/m^3$)	210

The snow depth in the table is defined perpendicular to the terrain. The above values of the snow depth in the two subareas correspond to an average of 3.25 m with a density $\rho = 200\,kg/m^3$ over the whole starting zone or 1.85 m with a density $\rho = 350\,kg/m^3$. This higher value of the density may be assumed to have been close to the density of the snow in the fracture line before the release of the avalanche. The average density of the snow in the deposit in 1995 was close to $\rho = 420\,kg/m^3$.

No entrainment was specified and therefore the total mass of the avalanche in the model is smaller than for the real avalanche. This is typical in avalanche models of this kind.

The results of a run of the dense flow model for Flateyri with the above specification of input parameters are displayed as coloured contour plots of the depth and velocity of the flowing avalanche at 10 s intervals (file fl.ppt on the attached CD). The modelled location and geometry of the deposit at the end of the run (denoted as "h6") is in a fair agreement with the outlines of the 1995 avalanche (fig. 1). The eastward margin of the deposit is close to the buildings at Sólbakki, in a good agreement with the observed outline of the avalanche. The western margin extends slightly further to the west than the observed outline. This may be caused by the retarding effect of the buildings in the village on the runout of the avalanche, but it could also be caused by slightly too high modelled velocities as the avalanche flows out of the gully at about 200 m a.s.l. The outline to the east of the gully at about 300 m a.s.l. seems to be too high and too far from the centerline of the gully compared with the measured outline, indicating too high velocities at that location of the path. The maximum velocity of the avalanche below the Skollahvilft gully is close to 60 m/s, which is higher than obtained with the Swiss 2D model for the 1995 avalanche (about 45 m/s). The channelisation of the avalanche as it flows into the gully and the direction of the avalanche out of the gully seem to be well modelled.

A coupled dense flow/powder flow simulation was also made for the 1995 avalanche from Skollahvilft using a rather high grain size parameter (2 mm) which leads to a comparatively little transfer of snow into the powder part of the avalanche. This is believed to be appropriate for Icelandic conditions. The results for the dense core of the coupled dense flow/powder flow model were essentially the same as for the previously described run with dense core model. Maximum powder pressures reached about 10 kPa in the gully at 2.5 m above the avalanche and 2-3 kPa in the uppermost part of the village.

It was concluded from the runs for Flateyri that the same input parameters can be used for the SAMOS model for Icelandic conditions as are traditionally used in Austria. The dense core model can be used without the powder part for modeling the dense core of avalanches without this leading to significant changes in the model results. The model appears to take the effect of the geometry of the avalanche path on the flow of the avalanche into account in a realistic manner. This applies to the channelisation of the flow into the gully, the spreading of the avalanche on the unconfined slope and the deflection of the avalanche when it flows at an angle to the fall line of the terrain. The modelled speed of the avalanche may be slightly too high although it is not possible to determine whether the speeds of the SAMOS model or the Swiss 2D model are more realistic without further analysis.

RESULTS FOR ÍSAFJÖRÐUR AND HNÍFSDALUR

Avalanche starting zones were defined in the mountains above the inhabited areas Ísafjörður and Hnífsdalur and also in the mountain immediatedly to the west of the settlement in Ísafjörður where an avalanche in 1994 destroyed many summer houses. A total of 21 different subareas were defined, 15 in Seljalandshlíð and Gleiðarhjalli to the north of the main settlement in Ísafjörður (labeled 1-15 on the maps), 1 above Kubbi to the south of the settlement in Holtahverfi in Ísafjörður (labeled 1), 4 on the north side of Hnífsdalur (labeled 1-4) and 1 on the south side of Hnífsdalur (labeled 5).

The main gullies in Seljalandshlíð and on the north side of Hnífsdalur, and the large unconfined slopes of Seljalandshlíð to the west of Seljaland, are believed to accumulate more snow than the starting areas in Kubbi and Gleiðarhjalli, and the unconfined mountainside at the south side of Hnífsdalur. The different snow accumulation conditions in the starting zones were described by classifying the zones into five snow depth classes as defined in the following table. The snow depth is defined relative to the specified snow depth in class I areas which are defined to be large deep bowls or gullies near the top of the mountain.

Class	Relative snow depth	Comment
I+	2	Deep and narrow gullies near the top of the mountain
I	1	Large deep bowls or gullies near the top of the mountain
II	2/3	Shallow bowls or relatively flat areas near the top of the mountain
III	1/2	Small and shallow bowls at comparatively low elevations
IV	1/4	Other parts of the mountain with a small snow accumulation potential

This classification is similar as the classification previously used in Bolungarvík, Neskaupstaður, Siglufjörður, Seyðisfjörður and Eskifjörður. Only classes I and III were used for the Ísafjörður and Hnífsdalur runs.

Eight runs with the SAMOS model were made in Ísafjörður and Hnífsdalur, two on the north side of the main settlement in Ísafjörður (run1n and run2n), two in Kubbi above Holtahverfi (run1k and run2k) and two on each of the north and south sides of Hnífsdalur (run1n, run2n, run3s and run4s). The first run in each pair of runs in each area were started with a uniform snow depth of 1.25 m in class I starting areas and the second run was started with a snow depth of 2.5 m in class I starting areas. The snow depth in all the runs was determined from the relative snow depth class for the respective areas as given in the above table.

The following table gives the total mass and volume of snow for each of the runs in Ísafjörður

Input	run1n	run2n	run3k	run4k
Snow depth in class I areas (m)	1.25	2.5	1.25	2.5
Total mass (10^3t)	278	557	8.5	17.0
Total volume (10^3m^3, $\rho = 200$ kg/m^3)	1392	2783	43	85

and the next table gives the total mass and volume of snow for each of the runs in Hnífsdalur

Input	run1n	run2n	run3s	run4s
Snow depth in class I areas (m)	1.25	2.5	1.25	2.5
Total mass (10^3t)	81	161	19.4	38.9
Total volume (10^3m^3, $\rho = 200\,\text{kg/m}^3$)	403	805	97	194

The mass and volume are total values for all the avalanches that were released simultaneously in the different starting zones. The snow was released simultaneously from the multiple starting zones in each run in order to simplify the model computations and in order to make them more economical in terms of computer time and time needed to set up the runs. This aspect of the simulations should not be taken to indicate that simultaneous release of this kind is likely to occur in nature.

The tables on this and the following page summarise the area and the relative snow depth for each of the starting zones in Ísafjörður and Hnífsdalur. The last column of the table lists the runs where snow was released from the zone.

Starting zone id	 name	Map area (10^3m^2)	Area (10^3m^2)	Relative snow depth	Runs
1	Seljalandshlíð, above Seljalandsdalur	454.8	552.7	1	1n,2n
2	Seljalandshlíð, above Seljalandsmúli	206.0	259.7	1	1n,2n
3	Karlsárgil	30.1	39.7	1	1n,2n
4	Grænagarðsgil	29.5	41.3	1	1n,2n
5	Hrafnagil	78.9	103.7	1	1n,2n
6	Steiniðjugil	15.1	20.3	1	1n,2n
7	Gleiðarhjalli, G1,2	25.9	35.0	1/2	1n,2n
8	Stakkaneshryggur	28.8	36.3	1/2	1n,2n
9	Gleiðarhjalli, G5	10.5	13.2	1/2	1n,2n
10	Gleiðarhjalli, G6	10.8	13.5	1/2	1n,2n
11	Gleiðarhjalli, G7	10.5	12.8	1/2	1n,2n
12	Stórurð	28.6	35.3	1/2	1n,2n
13	Gleiðarhjalli, G9,10	10.4	13.1	1/2	1n,2n
14	Gleiðarhjalli, G11	9.2	11.8	1/2	1n,2n
15	Gleiðarhjalli, G12,13	14.0	17.8	1/2	1n,1n
1	Kubbi	49.1	67.9	1/2	1k,1k
Total		580.8	740.0	—	—

It should be noted that avalanches from some of the starting zones in Ísafjörður and Hnífsdalur, particularly for zones 4 and 5 in Seljalandshlíð, some of the zones in Gleiðarhjalli, and zones 1 and 2 on the north side of Hnífsdalur, interact with neighbouring avalanches and this leads to longer runout than would otherwise be obtained. It should also be noted that starting zones 1 and 2 in Seljalandshlíð, the starting zone in Kubbi and the starting zone in Bakkahyrna cover large areas. One may expect that several independent avalanches, extending over a part of the area each, will in most cases be released rather than a single avalanche encompassing the entire area. Thus, the runout indicated by the SAMOS simulations for these runs for avalanches from these starting zones may be somewhat too long. However, observed avalanches from zone 1 in Seljalandshlíð have been released from almost the entire delineated starting area.

As in the simulations for Flateyri described above, and in separate reports for other villages in Iceland, snow entrained in the lower part of the path is not considered in the computations. Therefore, the volume of the avalanches from each starting zone is smaller than for real, large

Starting zone id	 name	Map area ($10^3 m^2$)	Area ($10^3 m^2$)	Relative snow depth	Runs
1	Hraunsgil	157.9	205.7	1	1n,2n
2	Between Hraunsgil and Traðargil	16.2	20.9	1/2	1n,2n
3	Traðargil	40.1	55.1	1	1n,2n
4	Búðargil	35.2	48.6	1	1n,2n
5	Bakkahyrna	121.8	155.7	1/2	3s,4s
Total		800.3	978.8	—	—

avalanches that might be released from the corresponding part of the mountain. Also, avalanches from starting zone 1 in Seljalandshlíð do not entrain snow from the large area in Seljalandsdalur before the edge of Tungudalur. This may be expected to lead to an underpredicted runout for avalanches from the starting zone in Seljalandshlíð above Seljalandsdalur.

The results of the eight runs are displayed as coloured contour plots of the depth and velocity of the flowing avalanche at 10 s intervals (files is_run1-2.ppt, isku_run1-2.ppt and hn_run1-4.ppt on the attached CD. The CD also contains similar files for other Icelandic villages where SAMOS computations have been carried out). Plots of the maximum dynamic pressure (given by $p = \rho u^2$) along the paths were also made (also on the CD). Some of the results are shown on figs. 3-22 (the flow depths are in m and the maximum pressure in kPa on the figures).

The runs illustrate a persistent tendency of the avalanches to form tongues below the main gullies in Seljalandshlíð in Ísafjörður and in Búðarfjall on the north side of Hnífsdalur.

The release volume ($\rho = 200\,\mathrm{kg/m^3}$) and runout index (Jónasson *et al.*, 1999) for the avalanches from the different starting zones for each of the eight simulations is summarised in the tables on the following page. The first of each pair of columns corresponds to a snow depth of 1.25 m in class I starting zones and the second column corresponds to a snow depth of 2.5 m in class I starting zones.

A runout index is not given in a few cases where interaction with avalanches from neighbouring starting zones makes it impossible to determine the runout of an avalanche from the starting zone in question.

It should be noted that the volumes given in the tables are not completely consistent with the volumes given in the previous tables that summarise the mass and volume of snow in each run. This discrepancy, which is in all cases less than 1-2%, is caused by discretisation errors in the computational grid because the delineation of the starting zones does not run along grid cell boundaries.

Previous simulations for Bolungarvík, Neskaupstaður, Siglufjörður, Seyðisfjörður and Eskifjörður (Jóhannesson *et al.*, 2001a,b, 2002a,b) showed that the large bowl shaped class I starting zones in Neskaupstaður release avalanches that reach a runout index in the approximate range 15.5-16.5 for a snow depth of 1.25 m and runout index in the range 17-18 for a snow depth of 2.5 m. The much smaller class I starting zones in Bolungarvík produced shorter avalanches that reached runout index 13.5-14 and 15-15.5 for snow depths of 1.25 and 2.5 m, respectively. The class II and III starting zones in Neskaupstaður produced avalanches with a runout similar as in Bolungarvík in some cases, whereas other starting zones, for example in Urðarbotn, released avalanches with an intermediate runout index of about 15 for runs with a class I snow depth of 1.25 m.

Avalanches from the deep and narrow gullies in Seljalandshlíð (particularly Hrafnagil where the avalanche merges with the neighbouring avalanche from Grænagarðsgil in the runout zone) and from Búðarfjall (Hraunsgil, Traðargil and Búðargil), reach very long runout. The runout ranges from about

Starting zone		Volume (10^3m^3)		Runout index	
id	name	run1/2	run3/4	run1/2	run3/4
1	Seljalandshlíð, above Seljalandsdalur	690.9	1381.7	15.9	16.3
2	Seljalandshlíð, above Seljalandsmúli	324.6	649.3	15.8	17.5
3	Karlsárgil	49.6	99.2	15.4	16.6
4	Grænagarðsgil	51.7	103.4	>17[1]	>18[1]
5	Hrafnagil	129.6	259.2	>17[1]	>18[1]
6	Steiniðjugil	25.4	50.7	14	15.3
7	Gleiðarhjalli, G1,2	21.9	43.8	14.0	15.6
8	Stakkaneshryggur	22.7	45.4	14.3	15.8
9	Gleiðarhjalli, G5	8.2	16.5	13-14	14-15
10	Gleiðarhjalli, G6	8.4	16.9	12.9	14.0
11	Gleiðarhjalli, G7	8.0	16.0	12.5	14.0
12	Stórurð	22.1	44.1	14	15.5
13	Gleiðarhjalli, G9,10	8.2	16.4	11.9	13.3
14	Gleiðarhjalli, G11	7.4	14.8	13.6	14.8
15	Gleiðarhjalli, G12,13	11.1	22.2	11.6	13.1
1	Kubbi	42.4	84.9	≈14	≈16
Total		1432	2865	—	—

[1] Avalanches from starting zones 4 and 5 in Seljalandshlíð are mixed into one tongue in the runout area. The runout indices for these two zones are therefore identical. The potential runout for avalanches from these zones is likely to be overpredicted by the SAMOS computations, particularly the runout from Grænagarðsgil that may be expected to be similar to the runout from the next gully to the west, Karlsárgil.

Starting zone		Volume (10^3m^3)		Runout index	
id	name	run1/2	run3/4	run1/2	run3/4
1	Hraunsgil	257.1	514.3	17.8	≈19
2	Between Hraunsgil and Traðargil	13.1	26.2	—	—
3	Traðargil	68.9	137.8	16.8	>18
4	Búðargil	60.8	121.6	16.4	18
5	Bakkahyrna	97.3	194.7	13.2	≈15
Total		497	995	—	—

[1] The avalanche from starting zone 2 between Hraunsgil and Traðargil flows into the tongue of the avalanche from zone 1 in Hraunsgil in the runout area. The runout indices for zone 2 are therefore not specified. The potential runout for avalanches from Hraunsgil may be slightly overpredicted by the SAMOS computations because of the mixing of avalanches from two zones.

16.5 to more than 17 for an initial snow depth of 1.25 m and from 18 to about or even over 19 for an initial snow depth of 2.5 m. In particular, the runout from Traðargil and Búðargil in Hnífsdalur, which have comparatively small starting areas of 5.5 and 4.9 ha, respectively, are surprisingly long. It does not seem reasonable that avalanches from these paths should reach much longer runout than avalanches that have previously been modelled from much larger starting areas in Neskaupstaður. There is, furthermore, no indication in the avalanche history that avalanches from these paths in Ísafjörður and Hnífsdalur are exceptionally long compared with avalanches from other large, hi-frequency paths in the country. The gullies in Ísafjörður and Hnífsdalur are characterised by very confined tracks all the way down to 100 m a.s.l. According to avalanche modelling practice in Switzerland one should increase the friction in the avalanche flow in strongly channelised paths of this type. This is not done in the SAMOS model. Here it is assumed that the long modelled runout in the gullies in Ísafjörður and Hnífsdalur reflects a deficiency in the SAMOS model in this respect.

The avalanche with an initial snow depth of 2.5 m from Seljalandshlíð above Tungudalur is not modelled to reach the observed runout of the avalanche that destroyed the summer houses in Tungudalur in 1994. The modelled runout of this avalanche may be too short because entrainment in the path along the comparatively flat Seljalandsdalur is neglected as mentioned before. It may also indicate that this avalanche was indeed exceptionally long.

The westernmost part of the avalanche with an initial snow depth of 1.25 m from Seljalandshlíð above Seljalandsmúli is deflected by the ridge and does not reach the lowland west of the apartment buildings in Seljalandshverfi. East of the apartment buildings, however, the avalanche is not significantly deflected and reaches runout index 15.8. This indicates that east of the apartment buildings in Seljalandshverfi the protective effect of the ridge does not significantly reduce the avalanche risk compared with the results of simple flowline models such as the PCM model. The avalanche with an initial snow depth of 2.5 m from Seljalandshlíð above Seljalandsmúli passes the ridge and flows over most of Seljalandshverfi east of Bræðratunga. This indicates that the Seljalandsmúli ridge does not provide sufficient protection against extreme avalanches for the lowland area between Seljaland and Bræðratunga.

The SAMOS modelling confirms that there is high avalanche danger below the gullies Karlsárgil, Grænagarðsgil, Hrafnagil and Steiniðjugil in Seljalandshlíð east of Seljaland. Avalanches from both model runs reach the sea and the areas between the gullies, where the avalanche danger can be considered lower than directly below the gullies, are small.

Below Gleiðarhjalli, avalanches from starting areas 7, 8 and 12 are modelled to have the longest runout. A tongue from starting area 14 is also modelled to have a relatively long runout. The avalanches from the starting zones below Gleiðarhjalli are all modelled to reach far into the settlement in spite of the reduced snow depth assumed in this area (class III, snow depth of $\frac{1}{2}$ relative to class I starting zones).

The avalanches from Kubbi and Bakkahyrna are also modelled to reach far into the settlement in spite of the reduced snow depth assumed in these areas (also class III).

The avalanche from Hraunsgil in Hnífsdalur is modelled to be split on the debris cone above the farm Hraun in a similar manner as indicated by the avalanche history. This is particularly evident in the plots of the maximum dynamic pressure. Avalanches are nevertheless modelled to be able to reach the farm.

There is an area near the old farm Heimabær between Traðargil and Búðargil where the avalanche danger may be expected to be much lower than directly below the gullies. The modelled direction of avalanches from Hraunsgil and Traðargil is, however, such that there is no area in the settlement between those gullies where the avalanche danger can be considered much lower than directly below the gullies.

The following conclusions may be drawn from the model results for Ísafjörður and Hnífsdalur:

1. Extreme avalanches from Seljalandshlíð above Seljalandsdalur are modelled to reach into the area of summer houses in Tungudalur. The SAMOS model may be expected to underestimate the runout of avalanches in this part of the mountain.

2. Extreme avalanches from Seljalandshlíð above Seljalandsmúli are modelled to reach the lowland in the entire area between Bræðratunga and Seljaland. The avalanche with the lower initial snow depth of 1.25 m deflected by the ridge and does not reach the lowland west of the apartment buildings in Seljalandshverfi. East of the apartment buildings, however, this avalanche is not significantly deflected and reaches well into the settlement.
3. There is high avalanche danger in Seljalandshlíð east of Seljaland below the gullies Karlsárgil, Grænagarðsgil, Hrafnagil and Steiniðjugil.
4. Avalanches from Gleiðarhjalli, Kubbi and Bakkahyrna are modelled to reach far into the settlement in spite of the reduced snow depth assumed in these areas (class III). Avalanche hazard below Gleiðarhjalli is greatest below starting areas 7, 8 (Stakkaneshryggur) and 12 (Stórurð).
5. There is high avalanche danger below Hraunsgil, Traðargil and Búðargil. The hazard is lower in the areas around the farms Hraun and Heimabær compared with other areas at a similar distance from the mountain due channelisation of the avalanche flow. The SAMOS model may be expected to overestimate the runout of avalanches from these gullies in Hnífsdalur as well as the runout of avalanches from the gullies in Seljalandshlíð east of Seljaland.

The persistent location of the main tongues in all the runs indicates that the simulated form of the tongues may be used to determine tongues in hazard lines in a hazard zoning of the village as was previously done for Bolungarvík, Neskaupstaður, Siglufjörður, Seyðisfjörður and Eskifjörður. Nevertheless, one should be careful not to overinterpret the tongue forms in the hazard zoning. Thus only an appropriate fraction of the runout differences between the central tongues and the intermediate areas indicated by the simulations should be used in the hazard zoning. The appropriate fraction to use is a matter of subjective judgement, but a value of about 1/2 could be used.

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