A surge of Skobreen, Svalbard

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Surging glaciers are common in Svalbard yet relatively few glaciers have been observed during a surge. This paper presents observations of the currently surging glacier Skobreen, in southern Spitsbergen. The study is based on examinations of new and archival photographs and maps. Skobreen, an 18 km^2 valley glacier terminating into the lower part of the glacier Paulabreen, has not been registered previously as a surging glacier. Skobreen experienced a build-up in its upper part, while there has been a lowering of the surface in the terminal region. Photographs from 1990 show incipient crevassing in the upper part. Photographs from 2003 show a slight advance of the terminus and marginal crevassing, indicating an initiation period of about 15 years for a surge of this glacier. In June 2005 transverse crevassing appeared in the upper part of the glacier, while the middle section moved as a block with strong shear margins and a pronounced drawdown of the ice surface. No traces of a surge front could be seen in the crevasse pattern. However, the crevasse pattern indicates an initiation area in the transition zone between the transverse crevassing in the upper part and the block of ice in the middle region.

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Glacier surges are characterized by cyclical advances related to internal changes in the glacier system rather than to climate change (Meier & Post 1969). The cause of these instabilities is still debated. Thermal trigger mechanism have been proposed (e.g. Schytt 1969; Clarke 1976), and changes in the subglacial drainage system are also thought to be important to the triggering of surges (Clarke et al. 1984; Kamb et al. 1985). The trigger mechanism has yet to be identified adequately but identifying the trigger zone will contribute to our understanding of the elements involved in a surge (Lawson 1996).

Surge-type glaciers represent only a small percentage of all glaciers and the phenomenon is highly concentrated in some glaciated regions (Raymond 1987). Surges constitute a common form of glacier advance in Svalbard (Liestøl 1969). From 13 % (Jiskoot et al. 1998) up to 90 % (Liestøl 1988; Lefauconnier & Hagen 1991) of the glaciers here are assumed to be surge-type. Nevertheless, relatively few glaciers have been observed during the active surge phase (Rolstad et al. 1997). The identification of surge activity is essential in the study of the duration of the active and quiescent phases of surging glaciers (Dowdeswell et al. 1995).

The initiation of a surge is normally seen as surface crevassing of the glacier in areas where crevasses have not been present earlier and/or by an advancing glacier tongue (Hagen et al. 1993). Crevasses are easily mapped on glaciers, for example, from aerial photographs. They are fundamentally important to the understanding and interpretation of glacier flow (Meier 1958; Whillans et al. 1993). Crevasses form in a perpendicular direction to the principal extending strain rate if the strain rate exceeds a threshold value (Nye 1952; Meier et al. 1974). Valuable information can be acquired from observations of the crevassing in an early stage of a surge. Later during the surge, the initial crevasse pattern will become

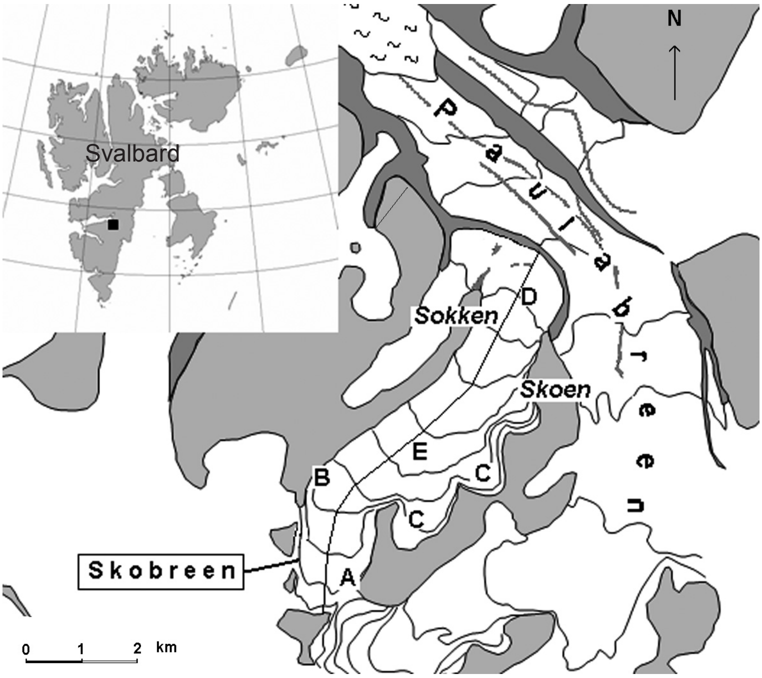

Fig. 1. The location of Skobreen. (A) marks the development of new crevasses in the bergschrund area; (B) marks the site marginal crevasses; (C) indicates the location of transverse crevasses; (D) is the site of a slight bulge in 2003; and (E) is the possible initiation area of the surge. Paulabreen terminates in Rindersbukta, Van Mijenfjorden.

more obscured. The location on the glacier at which the surge motion is initiated is one of the basic spatial properties of a surge. Determination of this location is based on an understanding of the relationship between surge behaviour and crevassing (Hodgkins & Dowdeswell 1994; Lawson 1997).

The objective of this paper is to document Skobreen's ongoing surge. Photographs of Skobreen during a surge—at a stage which makes it possible to interpret its surge dynamics—are presented. An additional objective is to pinpoint an initiation area through the crevasse pattern and to describe the recent build-up phase using various available sources.

Skobreen

Located at 77° 42'N, 17° 03'E, Skobreen is a 8.2 km long valley glacier with a drainage basin of 18.2 km^2 (Hagen et al. 1993) in Heer Land in southern Spitsbergen (Fig. 1). The glacier flows north-eastward, towards the lower part of the glacier Paulabreen, a 16 km long surge-type tidewater glacier (Hagen et al. 1993) feeding into the bay Rindersbukta at the head of Van Mijenfjorden. The upper part of Skobreen can be divided into one main basin, followed by three sub-basins along the south-eastern side. The elevation ranges from approximately 200 to 800 m a.s.l., and the ELA is estimated at 400 m a.s.l. (Simões 1990). Mountains from 500 to 890 m a.s.l. surround the glacier, which overlies approximately horizontal Tertiary and Cretaceous sedimentary rocks (Salvigsen et al. 1989).

Skobreen was surveyed by radio-echo sounding (RES) in 1985 and 1986 by a team from the Scott Polar Research Institute (Drewry 1985, 1987). A rock sill was found near the glacier terminus (Drewry 1987) and the mean ice thickness of the glacier was determined to be 135 m (Simões 1990). Most Svalbard glaciers are classified as polythermal (Schytt 1969; Liestøl 1988) and Skobreen has been assumed to have a polythermal regime (Drewry 1985; Simões 1990). Skobreen has not previously been registered as a surge-type glacier (Simões 1990; Hagen et al. 1993). However, the glacier was found to be extremely sensitive to small variations in air temperature. Simões (1990) concluded, based on this and the RES, that the possibility of surge behaviour, with a long quiescent phase, could not be ruled out. The moraine in front of the snout of Skobreen is classified as a lateral moraine of Paulabreen that has been pushed by Skobreen some time in the past, and not as a terminal moraine of Skobreen (Simões 1990).

Data sources and methods

Two sets of oblique aerial photographs covering the entire Skobreen were obtained during commercial flights on 14 June 2005 and 20 July 2005. A digital camera with 4 megapixel resolution was used. The photographs were taken from an altitude of approximately 1500 - 2000 m a.s.l. Slide photographs taken during a flight on 9 September 2003 have also been examined—these images cover only the terminus of Skobreen and Paulabreen on account of fog. M. Jochmann from Store Norske Spitsbergen Kullkompani (SNSK) provided a photograph from 25 August 2003. The Norwegian Polar Institute's (NPI) archive of vertical aerial photographs from various years was also studied (some photographs only cover part of the glacier). The contrast in the snow in the 1970 images is very good and is also rather good in the 1990 photographs. All photographs are listed in Table 1. It is also worth mentioning that a camera set up by The University Centre in Svalbard, in cooperation with SNSK, documented an advance (not "surge", as stated on the website at www.unis.no/research/geology/projects.htm) of Paulabreen's front from 21 April to 15 August 2005.

The NPI's 1 : 100 000 topographic map *C10 Braganzavågen* (NPI 1983), on which Skobreen appears, is based on a photogrammetric compilation of oblique aerial photographs from 1936 (and 1938). A new unpublished map made on the basis of 1990 aerial photographs was also obtained. Longitudinal profiles of the glacier centreline were drawn on the two maps (Figs. 1, 2). The quality of the older maps based on the oblique aerial photographs is dependent on the object's distance from the camera. In this case, Skobreen is rather close and the typical error in height is ±2.5 m, while the horizontal error is 20 m (T. Eiken, pers. comm. September 2005). Comparison of the contour lines on bedrock on the 1936 and 1990 maps indicates that the error in the old map is no more than 10 m.

Results

Quiescent phase

A notable feature of the Skobreen–Paulabreen interaction is the rather stable position of the terminus and moraine in front of Skobreen during the studied period, 1936–1990. The moraine is more pronounced in the 1990 photographs, indicating a slight lowering of the glacier terminus. Several supraglacial channels on Skobreen are visible on the various aerial photographs of the glacier: three main channels draining from the upper part and two channels that cross the moraine to Paulabreen. The location of these channels is very much the same in the different years, indicating stable conditions. The stable termini of Skobreen and Paulabreen, together with the integrity of the meltwater channels, suggest little activity in the lower parts of both glaciers prior to the present surge.

The stable termini of Skobreen and Paulabreen, together with the semicircular shape of the Skobreen moraine and the integrity of the meltwater channels, suggest low velocities and little activity

Table 1. Photographs used in this study.

Year	Date	Source	Angle or scale	Number	Remarks
1936	–	NPI	oblique	S36 2340 - 2344	3000 - 3500 m a.s.l.
1956	–	NPI	oblique	S56 0536 - 0539	covers only the lower part
1961	15 Aug	NPI	1 : 40 000	S61 2995 - 2996	covers only the upper part
1970	23 - 25 Aug	NPI	1 : 17 000	S70 4617 - 4618	
1977	16 Aug	NPI	1 : 20 000	S77 0892	covers only a part
1990	25 Aug	NPI	1 : 50 000	S90 6826 - 6827	
2003	25 Aug	M. Jochmann			covers only the terminus
2003	9 Sep	M. Sund			covers only the terminus
2005	14 Jun	M. Sund			
2005	20 Jul	M. Sund			

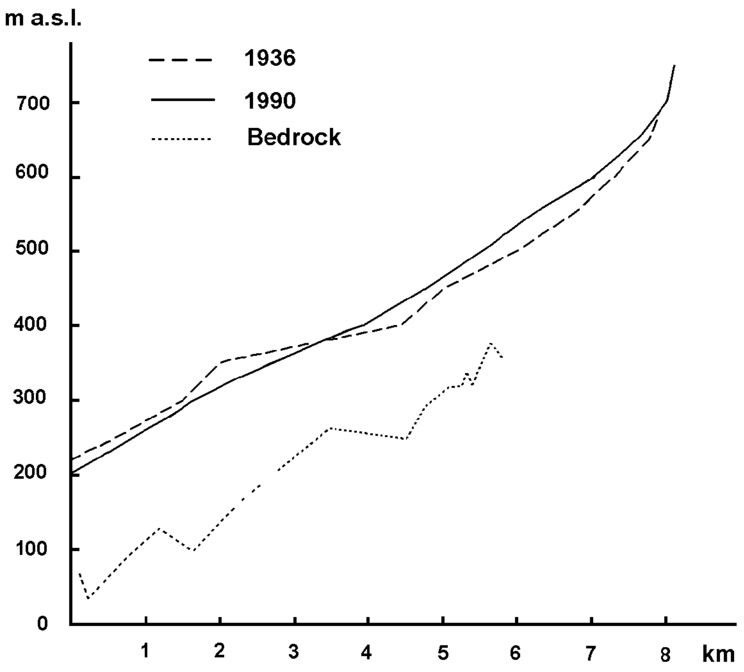

Fig. 2. Longitudinal surface profiles drawn from the 1936 and 1990 maps. Bedrock is drawn after Drewry (1985, 1987).

in lower parts of both glaciers prior to the present surge. It is not clear when Paulabreen's last surge took place, but several previous surges of the Paulabreen system (including the tributary glaciers) have been described (e.g. Hald et al. 2001). In 1898 the terminus of the Paulabreen system stood near the outlet of Rindesbukta (Murray et al. 1998). Photographs from 1936 show that a few decades later the terminus had retreated some 4 km, and it continued to retreat until very recently. In total this retreat measures about 14.5 km. This rapid retreat could indicate that the glacier system surged not too long before 1898. An interval of 30 (Lefauconnier & Hagen 1991) to 500 years (Dowdeswell et al. 1991) has been suggested as the duration period of the quiescent phase for Svalbard glaciers, depending in part on the rate of snow accumulation (Dowdeswell et al. 1995). As no indications of a previous surge have been found during the last century (Simões 1990; Hagen et al. 1993) there is reason to believe that the Skobreen has a build-up phase of 100 years or more.

The longitudinal profiles of Skobreen from 1936 and 1990 (Fig. 2) show a decreasing ice thickness below 380 m a.s.l. Above this, there has been a build-up during the same period. Data (not shown) from the uppermost part are more uncertain as the glacier ends in a steep hillside. The average change in thickness above 350 m a.s.l. is about 24 m. Given the area of the glacier above this elevation (6.34 km^2), this implies a build-up of about 0.155 km^3 of ice in the upper part of the glacier. Simões (1990) found that the mean annual accumulation rate during the years 1967–1986 was 0.33 m a^{-1} water equivalent. The difference between the profiles illustrates a typical pattern of a Svalbard surge-type glacier during a build-up phase. The 1936 profile reveals the combination of a convex feature in the lower part at 350 m a.s.l. followed by a flat surface 2.5 km up the glacier to 400 m a.s.l. Another bulge is found at the 450 m level.

Initiation

Generally, the 1936, 1961 and 1970 photographs show very little crevassing. There are only a very few bergschrunds in the upper areas. From 1970 to 1990 there is a difference in the crevasse pattern, but only a few of the crevasses can be attributed to variations in the snow cover. The major areas of crevassing are distinct in the 1990 photographs and totally absent in the 1970 photographs, indicating that they are new. The development of additional crevasses in the bergschrund area (marked A on Fig. 1) and small incipient marginal crevassing (B) approximately 2 km from the head along the western margin and in the eastern margin in the main basin, as well as the development of transverse crevassing (C) in the two uppermost sub-basins, can be seen. This is best observed by comparison with the 1970 photographs. The presence of these marginal crevasses is probably the first sign of the glacier decoupling from the bedrock. The incipient crevassing of the sub-basins (C) in 1990 support these indications.

A slight advance of the moraine in front of Skobreen can be seen on the 9 September 2003 photographs in comparison to the 1990 photographs. The 25 August 2003 photograph confirms this advance, showing traces of marginal shear against the mountain walls in the lower part of the glacier. However, there are no visible crevasses in the terminus area. From these photographs the advance is estimated to 200 to 400 m. A slight bulge (marked D on Fig. 1) can also be seen. The use of Paulabreen as a snowmobile track is clear evidence that the advance at this stage was still limited as no changes were reported during the 2003 or 2004 seasons. Skobreen is not commonly visited or particularly noticeable when passing by via Paulabreen and changes of Skobreen's upper reaches would not necessarily be observed.

Surge phase

The first recent glaciological change noted in the Rindersbukta area was the advancing glacier front of Paulabreen, observed by a tourist guide in March 2005 (Hanne C. Christiansen, pers. comm. June 2005). Independently, observations were made and photographs were taken during a flight to Svalbard on 14 June 2005 (Fig. 3a), revealing that the advancing front of Paulabreen originated from the progressing terminus of Skobreen and that there was extensive crevassing along this glacier. These signs indicate an active surge (Liestøl 1969; Meier & Post 1969). No crevasses could be seen on Paulabreen further up from the Skobreen–Paulabreen interaction.

Transverse crevasses on Skobreen can be seen from the upper area and down to the middle section, partly appearing as huge chasms as the ice from the basins flows into the main ice body in area E (Fig. 1). The middle section has a rather even surface, quite undisturbed by crevassing at this stage. The first set of photographs was taken at the beginning of the melt season; crevasses in this area could therefore have been hidden under the snow cover. However, the second set of pictures (Fig. 3b), taken more than a month later, still does not reveal crevassing of the same magnitude as further up or down this section. The western side of the glacier has no basins and shows a pronounced draw down of the ice. From the photographs, the general lowering of the surface at this stage is estimated to be 40 - 50 m. Approximately 6.5 km from the head of the glacier, on the eastern side, a pronounced shear margin is found where debris is squeezed up along the mountainside. All the differential movement occurs in a narrow zone at the glacier margins. The presence of a sharp debris-laden shear margin indicates that a uniform block flow has occurred across glacier. Further downwards of the block the crevassing again intensifies, partly also into a more mixed pattern, as the tongue curves 90º around the mountain ridge Sokken and drains further down and west into Paulabreen. The shear margin is also visible at the confluence with Paulabreen. However, the moraine in front of Skobreen is pushed forward almost undisturbed (Fig. 3c).

Discussion

The bulges in the 1936 profile could be a part of the build-up pattern of Skobreen during its quiescent phase. On Hessbreen, 55 km west–southwest of Skobreen, there were indications of a build-up as a result of smaller bulges propagating slowly down the glacier (Sund & Eiken 2004).

The initiation of surges in Svalbard can be a slow process developing through several years (Murray et al. 1998; Murray et al. 2003; Sund & Eiken 2004) and is often followed by a longer surge period (Dowdeswell et al. 1991; Murray et al. 2003), unlike glaciers with a faster initiation, for example, in Alaska (Harrison et al. 1994; Lawson 1997). Hessbreen's surge showed that even when crevasses began to open in the upper area of the glacier, the tongue remained unaffected (Sund & Eiken 2004). Much the same progress is found at Skobreen. This suggests that the initiation phase of this surge of Skobreen lasted for about 15 years.

For several glaciers the active phase of the surge cycle has been characterized by a surge front propagating down glacier (e.g. Echelmeyer et al. 1987; Clarke & Blake 1991; Lawson 1997; Murray et al. 1998). From the 1990 profile, no

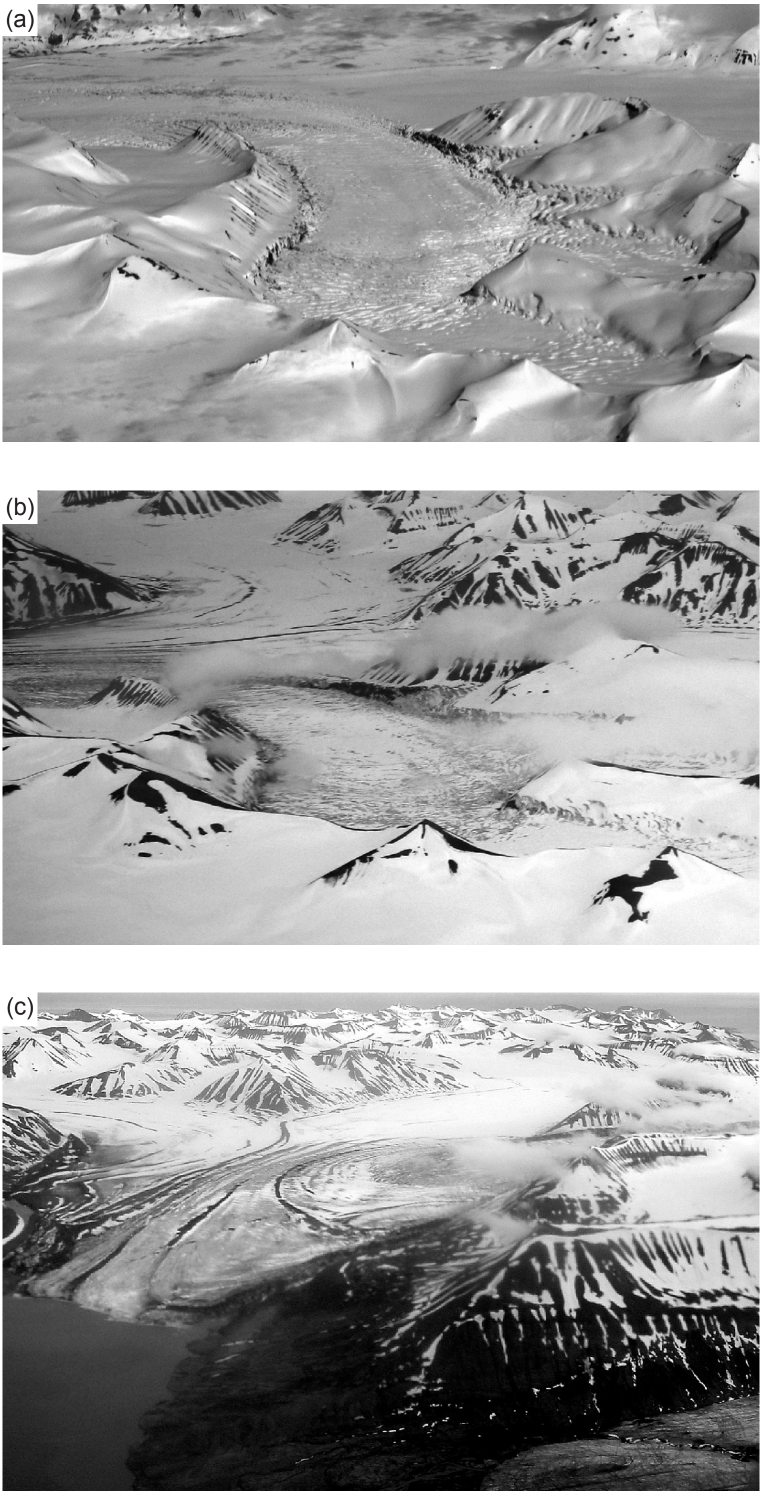

Fig. 3. The effects of the surge of Skobreen. (a) View of Skobreen toward the north-east, photograph taken on 14 June 2005. Notice the draw down along most of the glacier. (b) View of Skobreen toward the north-east; picture taken on 20 July 2005. (c) The terminus of Paulabreen and Skobreen; view is toward the south-east, photograph taken on 20 July 2005.

surge front or bulge could be identified. Surge fronts developing in the accumulation area and propagating down glacier leave a chaotic crevasse pattern in both longitudinal and transversal directions, due to compressing and extending forces (Clarke & Blake 1991; Lawson 1996). The appearance of transverse crevasses indicates there is no propagation of a surge front (Lawson 1996; Murray et al. 2003). The shear zone observed during the surge of Skobreen indicates a predominant contribution of basal sliding to surge motion (Echelmeyer et al. 1987). This feature is also found in a number of other actively surging glaciers in Svalbard (Pillewizer 1939; Meier & Post 1969; Rolstad et al. 1997; Sund & Eiken 2004). The presence of transversal crevasses followed by a shear zone and block flow down glacier implies there no evidence of a propagating surge front on Skobreen. The slight bulge feature (marked D on Fig. 1) found in Skobreen is likely to have been formed by the progressing block of ice decelerating and aggregating on to slower ice at the terminus of Skobreen and Paulabreen. Thus, formation is a result of the steadily proceeding mass of activated ice, which is different to a surge front propagating down glacier having a causal relationship to the origin of the surge.

On Variegated Glacier, in Alaska, transverse crevassing was found further up from where the surge was believed have been initiated (Lawson 1996). Hessbreen experienced heavy transverse crevassing in its upper part followed by a block movement further down glacier. The surge was probably initiated in the upper region of this block (Sund & Eiken 2004). If the behaviour of Skobreen is consistent with the results from Variegated Glacier and Hessbreen, the surge of Skobreen was initiated around the location marked E on Fig. 1.

Summary

From 1936 to 1990, Skobreen experienced a build-up in the upper part, while there has been a reduction of ice thickness in the lower area. The 1936 profile shows bulges which could be a part of the build-up pattern of the glacier. The smooth 1990 profile has no indication of such bulges. The quiescent phase is assumed to have lasted for more than 100 years. Comparisons of the 1970 and 1990 vertical aerial photographs reveal incipient crevassing in the upper area in 1990, probably consistent with the initiation phase of a surge. Photographs from 2003 show a slightly advancing moraine and marginal crevassing in the lower part of the glacier. Observations during the summer of 2005 showed that Skobreen, not previously registered as a surge-type glacier (Hagen et al. 1993), was actively surging. There were large crevasses in the upper part followed by a block of ice with strong shear margins advancing into and pushing the terminal part of Paulabreen. The surge is therefore categorized as a block surge (Pillewizer 1939). The transition between the crevassed upper part and the lower block is proposed to be the initiation area.

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