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Tidewater glaciers of Svalbard: Recent changes and estimates of calving fluxes

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Abstract: The purpose of this study is to describe the current state of tidewater glaciers in Svalbard as an extension of the inventory of Hagen *et al*. (1993). The ice masses of Svalbard cover an area of *ca* 36 600 km^2 and more than 60% of the glaciated areas are glaciers which terminate in the sea at calving ice-cliffs. Recent data on the geometry of glacier tongues, their flow velocities and front position changes have been extracted from ASTER images acquired from 2000–2006 using automated methods of satellite image analysis. Analyses have shown that 163 Svalbard glaciers are of tidewater type (having contact with the ocean) and the total length of their calving ice-cliffs is 860 km. When compared with the previous inventory, 14 glaciers retreated from the ocean to the land over a 30–40 year period. Eleven formerly land-based glaciers now terminate in the sea. A new method of assessing the dynamic state of glaciers, based on patterns of frontal crevassing, has been developed. Tidewater glacier termini are divided into four groups on the basis of differences in crevasse patterns and flow velocity: (1) very slow or stagnant glaciers, (2) slow-flowing glaciers, (3) fast-flowing glaciers, (4) surging glaciers (in the active phase) and fast ice streams. This classification has enabled us to estimate total calving flux from Svalbard glaciers with an accuracy appreciably higher than that of previous attempts. Mass loss due to calving from the whole archipelago (excluding Kvitøya) is estimated to be 5.0–8.4 km^3 yr^{-1} (water equivalent – w.e.), with a mean value 6.75 ± 1.7 km^3 yr^{-1} (w.e.). Thus, ablation due to calving contributes as much as 17–25% (with a mean value 21%) to the overall mass loss from Svalbard glaciers. By implication, the contribution of Svalbard iceberg flux to sea-level rise amounts to *ca* 0.02 mm yr^{-1}. Also calving flux in the Arctic has been considered and the highest annual specific mass balance attributable to iceberg calving has been found for Svalbard.

Key words: Arctic, Svalbard, tidewater glaciers, calving flux, ASTER.

Introduction

Climate warming is more pronounced in the Arctic than in the mid-latitudes (*cf.* ACIA 2005, IPCC 2007). The response of glaciers to climate change is a good measure of long-term climate trends and the environmental consequences of warming. There is much evidence that Svalbard glaciers are very sensitive to climatic change, presumably because the influence of the North Atlantic ocean current system (Walczowski and Piechura 2006). The ice masses of Svalbard cover an area of *ca* 36 600 km^2 and are among the largest glaciated areas in the Arctic (Hagen *et al*. 1993; Dowdeswell and Hambrey 2002). Glaciers that flow into the sea and terminate in an ice cliff from which icebergs are discharged are called tidewater glaciers (Van der Veen 1996) and the breakage of icebergs from the cliff is termed "calving". The term calving glaciers is also used; these are defined as glaciers calving brash and icebergs into lakes, fiords or open sea (Post and Motyka 1995). Tidewater glaciers are a characteristic feature of the Svalbard environment. They constitute more than 60% of the total ice-covered area. A recent study by Dowdeswell *et al*. (2008) indicates that calving from the Austfonna ice cap (8120 km^2) on Nordaustlandet, NE Svalbard alone amounts to 2.5 km^3 yr^{-1}. This represents as much as 30–40% of the annual ablation from this ice cap. This is a general indication of the importance of tidewater glaciers for the mass budget of Svalbard ice masses.

Climate warming affects tidewater glaciers through changes in the surface mass balance components, the dynamic response of glaciers, and the influence of warmer water on the ice cliff – ocean water interface. Generally, without taking into account active surges of glaciers discussed later in this paper, increased production of icebergs is a result of the dynamic response of glaciers terminating in the ocean to a warmer environment. Such a process has been evident in Greenland over the last few years (*e.g.* Dowdeswell 2006; Rignot and Kanagaratnam 2006; Nettles *et al*. 2008). The greater the transfer of glacier ice from land to the sea, the greater the eustatic sea level rise. We consider that this effect was underestimated by the last IPCC Report (IPCC 2007).

Svalbard glaciers contribute to global sea level rise because of their negative mass balance. Mass loss due to calving is still not properly studied. Existing estimates of the volume of icebergs lost by calving are both rather crude (Dowdeswell 1989; Lefauconnier and Hagen 1991; Hagen *et al*. 2003a; Dowdeswell and Hagen 2004) and variable, presumably due to the limited availability of data. To better estimate the mass of ice calved by tidewater glaciers in Svalbard, more data about the glaciers themselves and processes responsible for calving are needed.

A detailed glacier inventory of the Svalbard archipelago was compiled by Hagen *et al*. (1993) in the "Glacier Atlas of Svalbard and Jan Mayen". But almost all of the data presented there were derived from topographic maps at a scale of 1:100 000 (prepared from aerial photos taken in 1936) and more recent aerial photographs taken before 1990. As a result of the retreat and thinning of tidewater glaciers in Svalbard observed since the beginning of the 20th century (*e.g.* Koryakin 1975; Jania 1988a, 2002; Hagen *et al*. 1993, 2005) this inventory needs to be updated. The aim of this paper is to document the current status of tidewater glaciers in Svalbard, especially in terms of the nature of their calving fronts and present dynamic state. The paper aims to continue the work of Hagen *et al*. (1993) focusing only on the tidewater glaciers. Glaciers draining into lakes with no contact with the sea are not considered.

Recent data on the geometry of glacier tongues, their flow velocities and front position changes have been extracted from satellite imagery. Characteristics of all tidewater glaciers of Svalbard were examined (see Appendix) and compared with data presented by Hagen *et al*. (1993). A more precise estimate of ice mass loss by calving from the whole archipelago is another objective of this work. The calculation of ice fluxes is based upon observations of calving glaciers on satellite images and very sparse ground survey data (published and unpublished). The main sources of data used are ASTER images acquired from 2000–2006, mainly in July and August (*cf*. Table 1). The relatively long intervals between acquisition dates for many ASTER image pairs are due to the infrequent breaks in the cloud cover in the ablation season.

Table 1

ASTER and Landsat 7 imagery (granules) used in this studies; No. – number of the scene as presented on Fig. 2; D – acquisition date: dd-mm-yyyy.

No.	Data Granule ID	D	No.	Data Granule ID	D
ASTER			ASTER		
1	AST_L1A.003:2007905507	24.07.2002	23	AST_L1A.003:2025232924	7.08.2004
2	AST_L1A.003:2003624865	25.07.2001	24	AST_L1A.003:2036235228	15.08.2006
3	AST_L1A.003:2007910399	25.07.2002	25	AST_L1A.003:2030183765	23.07.2005
4	AST_L1A.003:2008754102	23.07.2002	26	AST_L1A.003:2035266221	20.07.2006
5	AST_L1A.003:2007905506	24.07.2002	27	AST_L1A.003:2029911899	6.07.2005
6	AST_L1A.003:2015776657	5.08.2003	28	AST_L1A.003:2007780347	11.07.2002
7	AST_L1A.003:2015776686	5.08.2003	29	AST_L1A.003:2003775114	5.08.2001
8	AST_L1A.003:2025232928	7.08.2004	30	AST_L1A.003:2030201287	24.07.2005
9	AST_L1A.003:2025232921	7.08.2004	31	AST_L1A.003:2008563292	5.07.2002
10	AST_L1A.003:2030183769	23.07.2005	32	AST_L1A.003:2007780343	11.07.2002
11	AST_L1A.003:2025232939	7.08.2004	33	AST_L1A.003:2007780342	11.07.2002
12	AST_L1A.003:2009046994	17.08.2000	34	AST_L1A.003:2007780344	11.07.2002
13	AST_L1A.003:2009046998	17.08.2000	35	AST_L1A.003:2007714526	12.07.2002
14	AST_L1A.003:2015312591	13.07.2003	36	AST_L1A.003:2003304043	16.06.2001
15	AST_L1A.003:2035244797	19.07.2006	37	AST_L1A.003:2003304045	16.06.2001
16	AST_L1A.003:2030183768	23.07.2005	38	AST_L1A.003:2030171638	18.07.2005
17	AST_L1A.003:2030183770	23.07.2005	39	AST_L1A.003:2030171637	18.07.2005
18	AST_L1A.003:2035364191	23.07.2006	40	AST_L1A.003:2003775127	5.08.2001
19	AST_L1A.003:2025153126	25.07.2004	LANDSAT 7		
20	AST_L1A.003:2025153125	25.07.2004	41	l71211004_00419990709	09.07.1999
21	AST_L1A.003:2025153146	25.07.2004	42	l71215002_00220010710	10.07.2001
22	AST_L1A.003:2016494057	27.07.2003	43	l72218003_00319990710	10.07.1999

The Svalbard glaciers

The Svalbard archipelago is located at the NW limit of the European continental shelf between 76.50–80.80°N and 10–34°E. It consists of four main islands: Spitsbergen, Nordaustlandet, Barentsøya, Edgeøya (Fig. 1) and *ca* 150 smaller islands. The total area of Svalbard is 62 800 km^2 and *ca* 60%, or about 36 600 km^2 of this area is covered by glaciers (Hagen *et al*. 1993). Various types of glacier are found. Dominant by area are the large continuous ice masses that are divided into individual ice streams by mountain ridges and nunataks. Small cirque glaciers are also numerous, especially in the alpine regions of western Spitsbergen. Several large ice caps are located in the relatively flat areas of eastern Svalbard. These ice caps calve into the sea. The total length of calving ice fronts in Svalbard is about 1000 km. All margins are grounded (Dowdeswell 1989). Maximum ice thicknesses of 500–600 m occur in Amundsenisen in South Spitsbergen and the Austfonna ice cap in Nordaustlandet. The total ice volume of Svalbard is estimated to be *ca* 7 000 km^3 (Hagen *et al*. 1993).

Permafrost conditions prevail in Svalbard and the depth of permafrost varies from 50 to several hundred meters. However, the glaciers in Svalbard are often polythermal, which means that some parts of the ice masses are temperate (at the pressure melting point) while other parts are at sub-freezing temperatures. In general the lower and thinner parts of the glaciers are frozen, to a depth of as much as 100 m. The consequence of this is that the thinner glaciers are often frozen to the ground. The thicker glaciers have temperate parts from which water drains throughout the year. Large icings are often formed in front of land-terminating polythermal glaciers when meltwater slowly drains out of the glacier during winter and freezes on the cold frozen ground. Winter drainage can often be observed in front of tidewater glaciers as an upwelling of water at the calving front.

Owing to the low ice temperatures and fairly low accumulation rates, the flow rate of Svalbard glaciers is generally low. In general, glaciers that terminate on land flow much more slowly than tidewater glaciers. Typical surface velocities are less than 10 m yr^{-1} close to the equilibrium line altitude of glaciers that terminate on land, whereas some calving glaciers have much higher velocities – 100 m yr^{-1} or more. Kronebreen in Kongsfjorden is by far the fastest flowing glacier in Svalbard, having a velocity of about 2 m d^{-1}, or 700–800 m yr^{-1} at the calving front.

Surging glaciers are common in Svalbard (Liestøl 1969; Jania 1988a; Lefauconnier and Hagen 1991; Hagen *et al*. 1993; Dowdeswell *et al*. 1991; Jiskoot *et al*. 2000). A surge event results in a large ice flux from the higher to the lower regions of a glacier, usually accompanied by a rapid advance of the glacier front and, in the case of tidewater glaciers, by increased iceberg production. For instance, the 1250 km^2 Hinlopenbreen, which surged in 1970, calved about 2 km^3 of icebergs in a single year (Liestøl 1973).

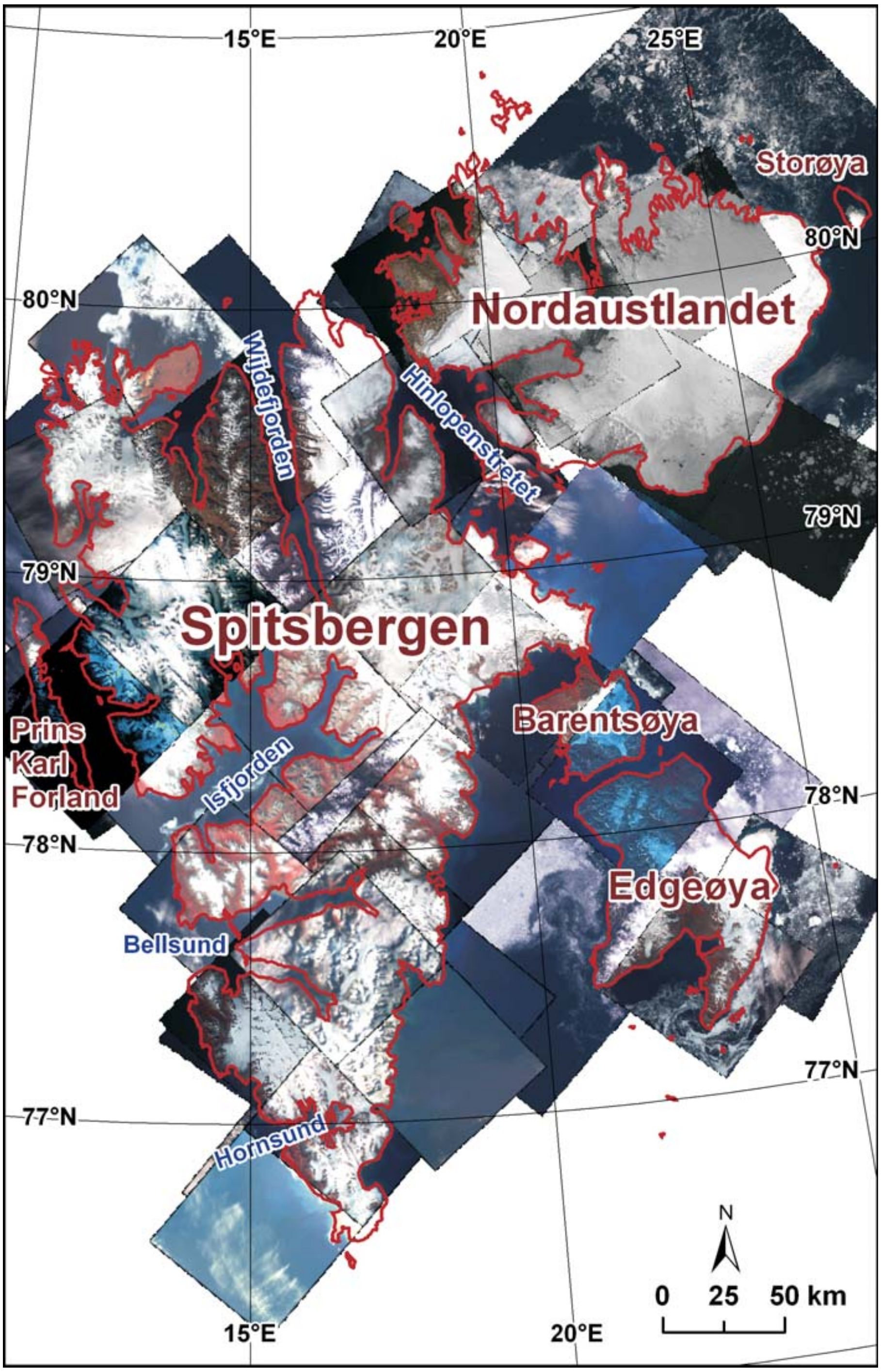

Fig. 1. Location map of Svalbard and glaciated area of the archipelago as visible on mosaic of ASTER and Landsat 7 images used in this study (*cf.* Table 1 and Fig. 2).

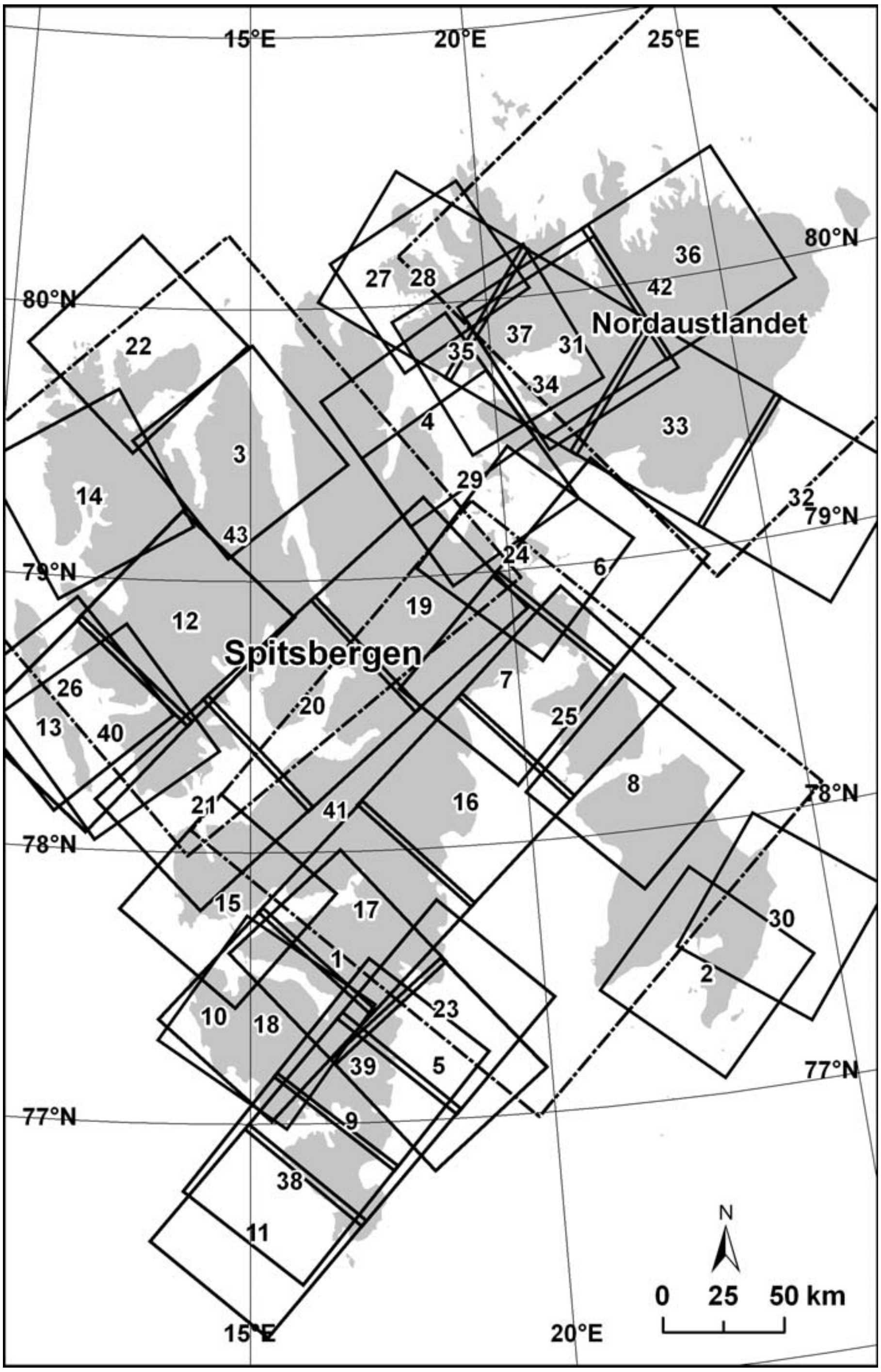

Fig. 2. Sketch of coverage of Svalbard by ASTER (solid frame) and Landsat 7 (dashed frame) imagery used in this inventory (Nos. of scenes correspond to Nos. in Table 1).

Observations of front positions indicate a general retreat of glaciers in Svalbard over the last 80 years. The Little Ice Age ended in Svalbard about 100 years ago, when most glaciers reached their maximum Holocene extent.

Annual mass-balance measurements have been made on several (<1%) Svalbard glaciers for up to 40 years. Consistent with the general recession, most of these glaciers have a negative mass balance, but with no discernible change in trend. The winter accumulation undergoes an inter-annual variations but they are fairly small. The mean summer ablation is also stable with no obvious trend. However, there are large inter-annual variations in the annual net mass balance and the summer ablation clearly controls these variations. While low-altitude glaciers are shrinking steadily, glaciers with high-altitude accumulation areas have mass balances closer to zero or even positive in some years.

Estimates of the total mass balance of Svalbard glaciers vary between -5 to -14 $km^3\ yr^{-1}$ or a specific net mass balance of -0.12 to -0.38 m yr^{-1}, equivalent to a sea level rise of 0.01 to 0.04 mm yr^{-1} (Hagen *et al*. 2003a, b). There are thus still large uncertainties about the overall mass balance and the calving flux. In this paper we will attempt to improve the latter estimate.

Methods

The optical sensor ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) on board the Terra satellite has proved to be a useful tool for glacier mapping and monitoring (*e.g*. Paul *et al*. 2002; Paul and Kääb 2005; Svoboda and Paul 2007; Bolch *et al*. 2008; Molnia 2008; http://www.glims.org/). ASTER imagery has relatively high spatial resolution in the visible and near visible IR bands (15 m and 30 m), and ASTER's along-track stereo sensor allows photogrammetric DEM generation. ASTER images have previously been used for studies of Svalbard glaciers (*e.g*. Dowdeswell and Benham 2003; Kääb *et al*. 2005; Kääb 2005). Owing to a dearth of cloud- and snow-free ASTER images of Svalbard, however, three Landsat 7 images were also used in this study. The images used are listed in Table 1 and shown on Figs 1 and 2, and were acquired over 7 summer ablation seasons.

The most important morphometric features of all tidewater glaciers are: (1) glacier area, (2) length of centerline, (3) glacier mean slope, (4) length of crevassed zone, (5) area of crevassed zone close to the active calving front, and (6) length of ice cliff. These features were measured on the geocoded ASTER and Landsat 7 images using *ArcGIS* software. The surface velocity fields of glacier termini were derived from ASTER image pairs and from published and unpublished ground survey data.

The delineation of glacier basins is crucial for a proper glacier inventory. The boundaries of the Svalbard tidewater glaciers were mapped automatically (Fig. 3a)

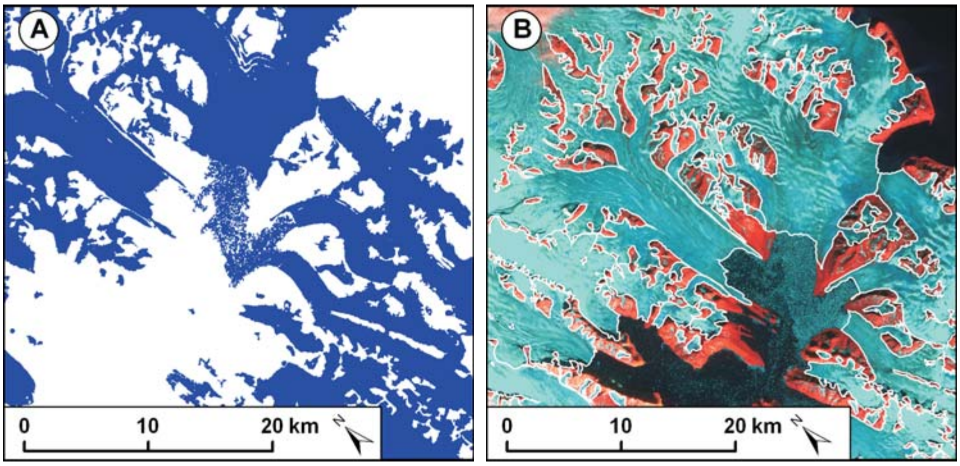

Fig. 3. Glacier boundaries for the southern area of Svalbard: a) ratio of two image channels (A4/A3) to obtain a glacier mask; b) manually mapped on FCC of ASTER (7.08.2004) bands 432.

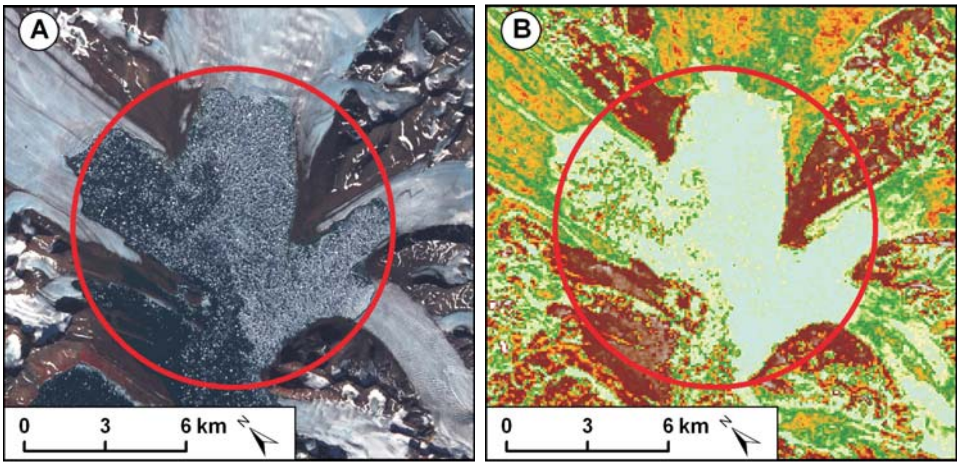

Fig. 4. Result of application of the Haralick method of texture analysis for distinction between dense icebergs and ice brash masses floating on the sea water and the glacier tongues surfaces. Brepollen in the eastern part of Hornsund Fiord, S Spitsbergen; a) FCC of ASTER (7.08.2004) bands 432; b) texture image – Difference entropy.

using the ratio of ASTER bands 3 (15 m resolution) and 4 (30 m resolution) to generate a glacier mask, and by automated raster line to vector conversion. A panchromatic False Colour Composite (FCC) of ASTER bands 432 was used to manually delineate those glaciers for which expert knowledge was needed (Fig. 3b).

In several cases, the definition of ice cliff lines by automatic classification of glacier areas was problematic because it was difficult to distinguish between the glacier and ice floating on the water (icebergs, ice brash probably mixed with sea ice-floes) close to the calving cliff (Fig. 4a). Textural analysis of the ASTER im-

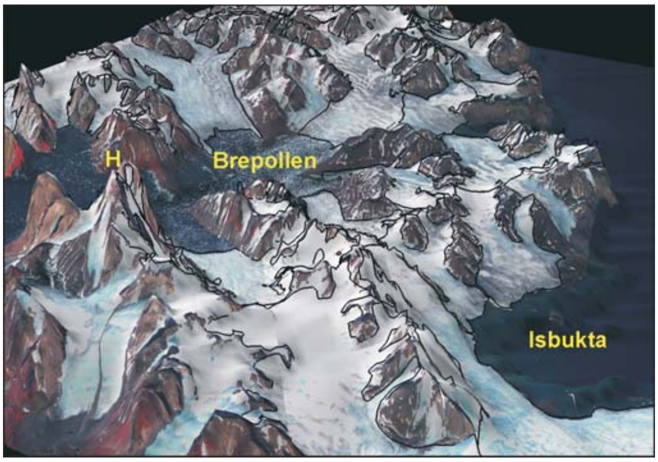

Fig. 5. Three dimensional view of glacier basins in SE Spitsbergen, processed from stereoscopic ASTER images (7.08.2004); vertical scale exaggerated 5x. The boundaries of basins are marked by solid lines. H – peak of Hornsundtind mountain 1431 m a.s.l.

ages (using *MaZda* software; Haralick *et al*. 1973; Rudnicki 2002) was used to distinguish the ice floating in the ocean from the glacier body (Fig. 4b).

DEMs prepared from the ASTER stereo bands (in *PCI Orthoengine* software) were used to delineate boundaries between individual glacier basins. Definition of glacier boundaries was achieved by visual supervision of the "watershed" procedure in the *ArcGIS* software system and other methods such as slope and aspect analysis (Fig. 5). In cases where slopes are low, as in the vicinity of ice divides and in ice cap interiors, the delineation of any particular glacier basin is difficult. The same is true in respect of glacier tributaries and confluences. In such cases, delineation is necessarily subjective (*cf.* Jania 1988b; Hagen *et al*. 1993). The length of the glacier along its centre-line, the length of the active calving front and the length of the terminal ice cliff were derived manually using *ArcGIS* software. Other specific methods applied in this study are outlined in subsequent paragraphs.

Inventory of tidewater glaciers

The inventory of tidewater glaciers listed in the Appendix contains an identification number for each glacier, the name of the glacier unit, information on the satellite imagery employed to map the glacier, data on the length and area of the glacier, the length and area of the terminal crevassed zone, the length of the terminal ice-cliff, the average ice-marginal retreat rate (area of glacier retreat divided by the length of the ice cliff), the retreat rate measured along the glacier center-line, a symbol for the glacier front type, and an estimate of the calving intensity (Table I in the Appendix).

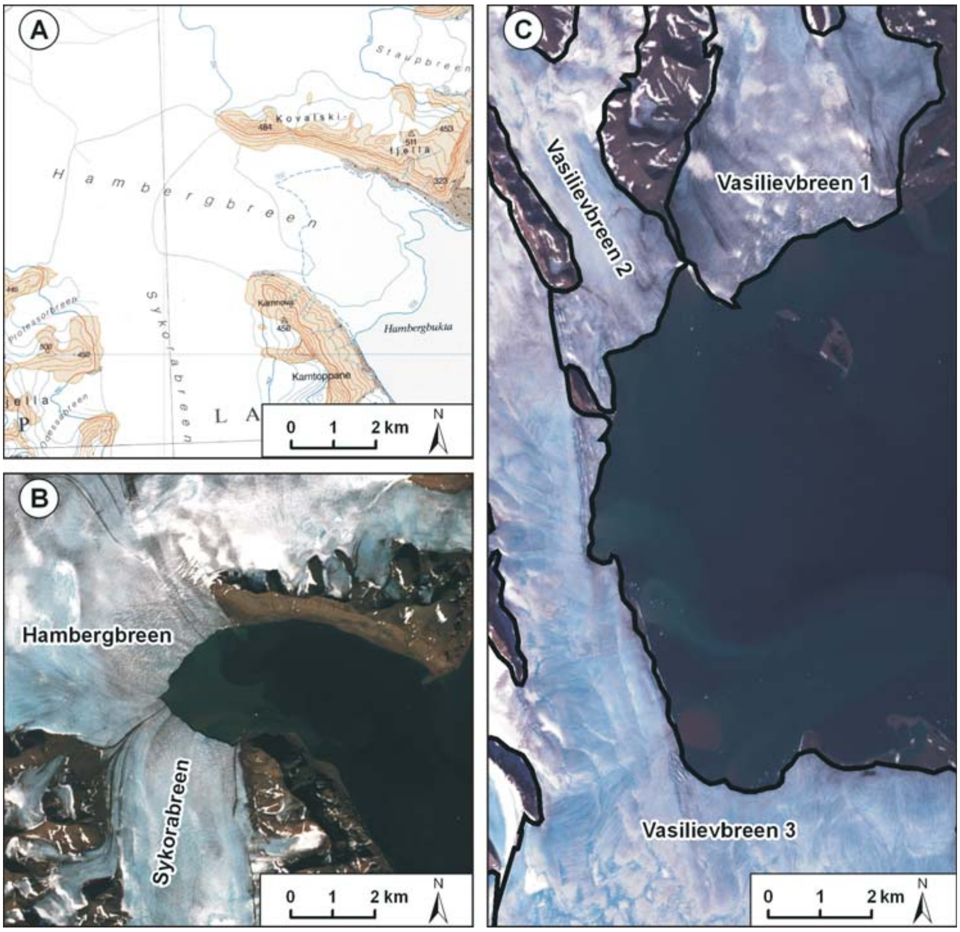

Fig. 6. Left: Hambergbreen (121 04) now separated into two components after retreat: Hambergbereen and Sykorabreen; a) front position in 1936, a portion of the topographic map 1:100 000, sheet C12 Markhambreen, courtesy of the NPI; b) ASTER image (7.08.2004); c) Vasilievbreen (121 04) now separated into three components following different dynamics of particular segments (ASTER, 7.08.2004).

The system used for the identification of glaciers in this work is the same as that used in Hagen's *et al*. (1993) inventory. It includes the number of regions of Svalbard (see Appendix: Fig. 12), the glacier identification number from the World Glacier Inventory (WGI) and the name of glacier basin. Some glaciers which were formerly confluent are now separated, owing to significant recession (Fig. 6a, b). Other glaciers that are still confluent have very different dynamics, in which case they are classified separately for the purpose of our inventory. They still have the common WGI identification number (Appendix – Table I), but are given either separate names derived from topographic maps (see an example on Fig. 6b) or consecutive numbers (for instance Vasilievbreen 1, Vasilievbreen 2, *cf*. Fig. 6c).

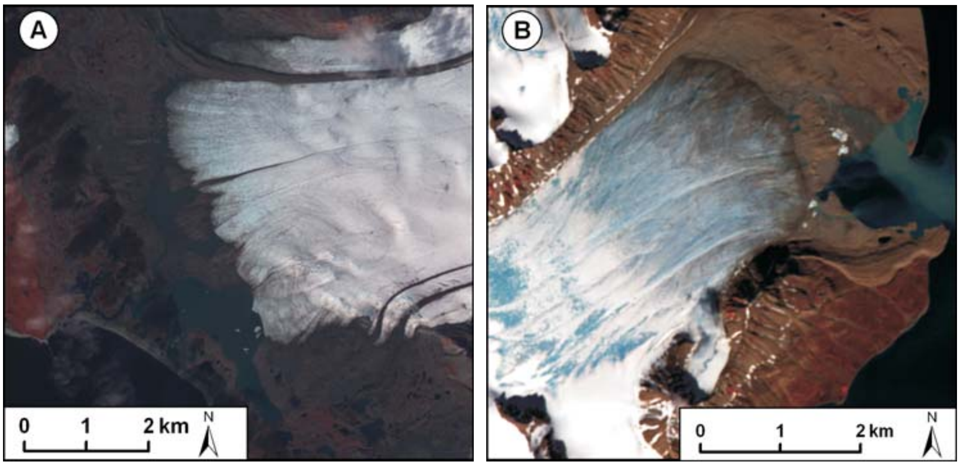

Fig. 7. Examples of analysis of glacier front type: a) Front of Eidembreen is in contact with a lake but is probably separated from the sea by a moraine (ASTER, 05.08.2001); b) Renardbreen retreated from the sea onto land (ASTER, 23.07.2006).

The inventory includes data on the area of the glaciers. It must be emphasised, however, that the "area of tidewater glacier" is defined differently from that of its "total basin". When a tidewater glacier has a compound basin, only that part of it feeding the calving front was taken into consideration and presented here as the "glacier area". This implies that tributary glaciers clearly separated from the main basin by moraines were not included in the "glacier area" measurements. Similarly, marginal sections of tidewater glaciers that terminate on land were not included in the area calculation. This reflects the general objective of this paper, which is the assessment of the dynamics of tidewater glaciers and the calculation of iceberg fluxes from them. As a result, data on the glacier area presented in the atlas of Hagen *et al*. (1993) are not directly comparable with the values presented in this inventory.

For the large ice caps of Nordaustlandet, the "areas of glacier basins" were taken from Hagen *et al*. (1993). Owing to incomplete ablation season coverage by ASTER scenes, Landsat 7 images were substituted for these areas. A consequence of this was that it was not possible to define ice divides and glacier borders by the method described earlier. The other parameters for that island were updated using the methods described earlier. Low-resolution ASTER images (150×150 m) available in the LP DAAC inventory (http://edcimswww.cr.usgs.gov/pub/imswelcome/) were used in the categorization of Kvitøyjøkulen (on the small island Kvitøya, NE Svalbard).

All fronts of Svalbard tidewater glaciers have been analyzed and compared with Hagen's *et al*. (1993) inventory. Detailed visual analysis of ASTER images (RGB – bands 321) enabled us to identify the present state of their termini (*i.e.* whether the glacier terminates on land or in the sea; Fig. 7, Fig. 10). In several cases, it was difficult to define the glacier state solely on the basis of an ASTER image *e.g.* Eidembreen (Fig. 7a). The tongue of this glacier has contact with a lake, but no canal can be identified between lake and sea on the 2001 ASTER image. Therefore this glacier was not identified as a tidewater glacier.

All glaciers terminating in the ocean at an ice-cliff longer than 150 m were classified as tidewater glaciers. Owing to shading by mountain ridges the fronts of some very small glaciers were hard to identify on ASTER images. Snow cover on, and the presence of sea-ice close to glacier fronts on some June images caused further classification problems.

In total, 163 glaciers were classified as tidewater glaciers in this study (Appendix – Fig. 12). This number includes 11 glaciers that were characterized as "land based" in Hagen's inventory, but which are now in contact with the sea. Presumably these glaciers either advanced into the sea or have retreated from a frontal moraine shoal or peninsula into deeper water. 14 glaciers characterized as "calving glaciers" by Hagen *et al*. (1993) no longer extend into the sea (Fig. 7b).

Fluctuations and dynamics of glaciers

ASTER image pairs acquired a minimum of one year apart provide a good overview of glacier front fluctuations. Nevertheless, inter-annual variations in the rate of terminus position changes of tidewater glaciers have to be surveyed carefully and their effects separated from those of seasonal fluctuations (winter advance and summer retreat). Our data analysis provides snapshots of margin position changes and confirms that most Svalbard calving glaciers are now in recession. We measured the average front fluctuation of 39 glaciers, for which pairs of summer ASTER images separated by several years are available (*cf*. Fig. 8). Results are shown in Table I (Appendix). Two methods of measurement were used: (1) front retreat along the glacier center-line and (2) average terminus retreat (area of that part of the glacier which has retreated, divided by the length of ice-cliff measured on the first image). The majority of glaciers in our survey have retreated at an average rate of 30–150 m yr^{-1}. Changes in the margin position of 9 glaciers were close to zero, while two glaciers have advanced (Vestre Torellbreen by 80 m in 2005–2006 and Chydeniusbreen by 200 m in 2001–2002).

Published data confirm a general recession of tidewater glaciers in Svalbard. The retreat of Hansbreen, for example, is as much as 40 m yr^{-1} (Jania 2006). Other glaciers flowing into Hornsund Fiord have retreated by 30–50 m yr^{-1} during the last few decades (Głowacki and Jania 2008), as have those draining Austfonna. Individual drainage basins of this ice cap retreated a few tens of meters per year on average, whereas the ice-cliff of Etonbreen retreated at an average rate of 120 m yr^{-1} (Dowdeswell *et al*. 2008). The front of Nathorstbreen retreated 14 km (*ca* 135 m yr^{-1}) between 1898 and 2002, with rates varying from 77 to 250 m yr^{-1} (Carlsen *et al*. 2003). The terminus recession of Aavatsmarkbreen was as much as 700 m (100 m yr^{-1}) during the period 2000–2006. Other glaciers in the Forland-

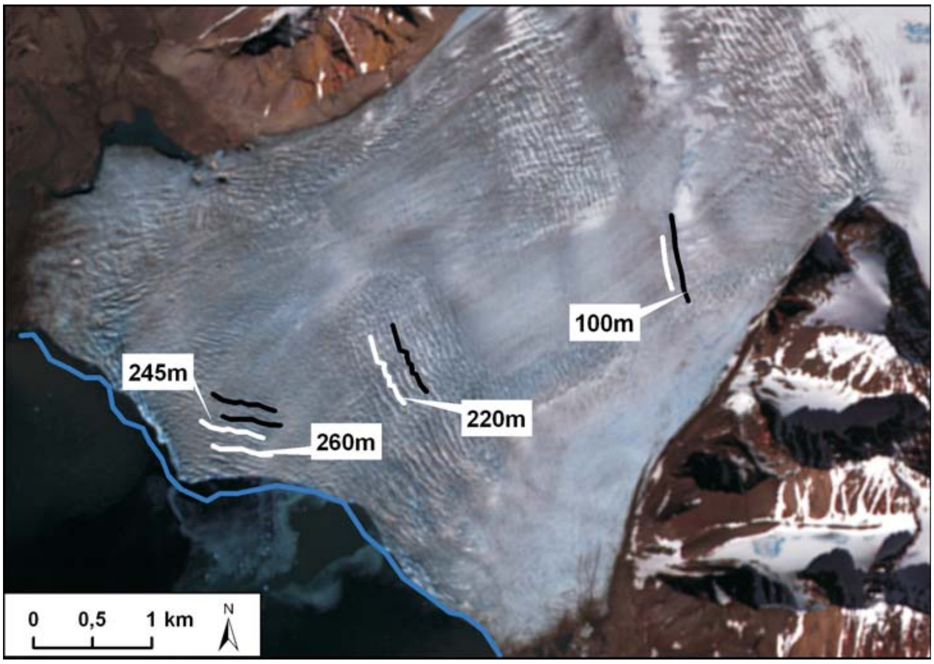

Fig. 8. Annual flow velocities on the Austre Torellbreen tongue derived from displacement of crevasses on a pair of ASTER images (2005 and 2006): black lines – location of crevasses in 2005, white lines – location of crevasses in 2006, blue line – front position in 2005. The background image is a portion of the FCC of ASTER scene (acquired on 23.07.2006).

sundet area (NW Spitsbergen): Konowbreen, Osbornebreen and Dahlbreen are also retreating relatively quickly (Grześ *et al*. 2008).

Nevertheless, several glaciers have surged at relatively rapid rates in recent times (*e.g*. Tunabreen, which advanced about 1400 m during the period 1999–2004). According to Dowdeswell and Benham (2003), the terminus of Perseibreen advanced at rate over 400 m yr^{-1} between June 2000 and May 2001 and this rate increased to over 750 m yr^{-1} between May and August 2001. From 1995 to 1998 the ice-front of Fridtjovbreen advanced 4000 m in 33 months (Lønne 2003). The average recession rate for the entire population of Svalbard tidewater glaciers was estimated as about 30 m yr^{-1}.

The flow velocities of tidewater glaciers vary on different time scales (diurnal, seasonal and interannual). Therefore, the time interval between measurements is an important influence on the results. Certainly, velocity data acquired over short time periods (*e.g*. by InSAR) are not necessarily representative of the annual mean velocity. There are few direct measurements of the velocity of Svalbard tidewater glaciers. Owing to a dearth of repeat ground survey measurements for areas close to glacier termini, a feature-tracking technique was applied to sequential ASTER imagery from 2000–2006 in order to determine surface velocities near several glacier fronts (Table 2).

Table 2

Mean flow velocity of Svalbard tidewater glaciers: * – glacier with very low velocity (see comment in the text), ASTER (MB) – after Błaszczyk (2008).

WGI No.	Glacier name	V [m yr^{-1}]	Survey date / period	Source of data
111 01	Pedasjenkobreen	<30*	2003–2005	ASTER (MB)
111 03	Sonklarbreen	<30*	2003–2005	ASTER (MB)
111 05	Negribreen	<30*	2003–2005	ASTER (MB)
115 01	Kvalbreen	<30*	2002–2004	ASTER (MB)
115 02	Strongbreen	<30*	2002–2004	ASTER (MB)
115 03	Perseibreen	730–910	2001 (active phase of surge)	Dowdeswell and Benham 2003
115 05	Jemelianovbreen	<30*	2002–2004	ASTER (MB)
124 04	Körberbreen	*ca* 400 90	1938 (active phase of surge) 2004–2005	Pillewizer and Voigt 1969 ASTER (MB)
124 07	Samarinbreen	115	2004–2005	ASTER (MB)
124 08	Chomjakovbreen	85	2004–2005	ASTER (MB)
124 09	Mendelejevbreen	<30*	2004–2005	ASTER (MB)
124 12	Storbreen	80	2004–2005	ASTER (MB)
124 17	Mülbacherbreen	210	2004–2005	ASTER (MB)
124 18	Paierlbreen	500	1996 (active phase of surge)	Vieli 2001
124 20	Hansbreen	150 130 55–70	1998, 1999 (0.8 km upstream from the ice-cliff) 2004–2005 2007–2008 (3.7 km upstream)	Vieli *et al.* 2002 ASTER (MB) GPS (Puczko pers. comm.)
125 03	Au Toreellbreen	260	2005–2006	ASTER (MB)
125 05	Ve Torelbreen	140	2005–2006	ASTER (MB)
131 16	Recherchebreen	<30*	2005–2006	ASTER (MB)
132 13	Zawadzkibreen	<30*	2005–2006	ASTER (MB)
132 17	Liestolbreen	<30*	2005–2006	ASTER (MB)
137 08	Fridtjovbreen	115 *ca* 900	1988 1996 (active phase of surge)	Glazovsky and Moskalevsky 1989 Murray *et al.* 2003a
149 01	Borebreen	<30*	2001–2004 (1.5 km upstream from the ice-cliff)	ASTER (MB)
153 13	Osbornebreen	250	2000–2001	ASTER (MB)
153 16	Gaffelbreen	70	2000–2001	ASTER (MB)
153 19	Dahlbreen	250	2000–2001	ASTER (MB)
154 04	Aavatsmarkbreen	33–50	2000 (July)	Jania *et al.* 2002
154 12	Comfortlessbreen	55	2001 (April)	GPS (Perski *pers. comm.*)
155 10	Kongsvegen	1.4–3.6	1996–2004	Hagen *et al.* 2005
155 11	Kronebreen	800 600	2001 1999–2002	Kääb *et al.* 2005

162 11	Monacobreen	700–800	1995–1996 (active phase of surge)	Murray *et al*. 2003b
172 14	Odinjokulen N	<30*	2001–2002	ASTER (MB)
172 15	Tommelbreen	<30*	2001–2002	ASTER (MB)
173 02	Sven Ludvigbreen	<30*	2001–2002	ASTER (MB)
174 04	Moltkebreen	<30*	2003–2006	ASTER (MB)
174 06	Hochstatterbreen	<30*	2003–2006	ASTER (MB)
211 08	nameless	238	1995 (winter)	Sharov and Etzold 2005
221 02	Palanderbreen	36–49	1996 (winter)	Sharov and Etzold 2005
222 08	Aldousbreen	95–142	1996 (winter)	Sharov and Etzold 2005
222 09	Frazerbreen	307	1996 (winter)	Sharov and Etzold 2005
222 10	Idunbreen	232	1996 (winter)	Sharov and Etzold 2005
232 03	S Franklinbreen	35–74	1995/1996 (winter)	Sharov and Etzold 2005
232 04	N Franklinbreen	14–49	1995/1996 (winter)	Sharov and Etzold 2005
241 03	Sabinebreen	<11	1995 (winter)	Sharov and Etzold 2005
242 01	Rijpbreen	128	1995 (winter)	Sharov and Etzold 2005
251 06	Duvebreen	170–205	1995 (winter)	Sharov and Etzold 2005
252 02	Nilsenbreen	84	1995 (winter)	Sharov and Etzold 2005

Several previous studies of the velocities of Svalbard glaciers have used this feature-tracking method (Lefauconnier *et al*. 1994; Rolstad *et al*. 1997; Dowdeswell and Benham 2003; Kääb *et al*. 2005). However, they only relate to fast-flowing and surging-glaciers, and used image pairs acquired only a short time apart. Only Kääb *et al*. (2005) derived an annual surface velocity field for the lowermost 10 km of the fast-flowing Kronebreen. For the present work, the available images were of sufficient quality and the time periods between successive ASTER image acquisitions were long enough that the frontal velocity fields of 27 glaciers could be measured for one-year and two-year periods.

The annual surface velocities of glaciers were derived from measurements of horizontal displacements of surface features (crevasses, supraglacial moraine elements) that could be unambiguously recognized on successive images. An example is shown in Fig. 8. In the absence of ground control-points, one ASTER image was used as the reference co-ordinate system for a second image. Dowdeswell and Benham (2003) suggested that the velocity error from this source is probably within a half to one ASTER pixel (7.5–15 m yr^{-1}). The estimated accuracy of velocity measurements derived from repeat ASTER images in this study is probably better than ± 30 m yr^{-1}.

For 16 very slow or stagnant tidewater glaciers, very small terminal crevassed areas were noted. For these glaciers there was no measurable surface velocity on ASTER images (15 m resolution) in the region near the glacier fronts, even over a two-years interval (marked with stars in Table 2). Such glaciers are probably in the quiescent phase of a surge cycle.

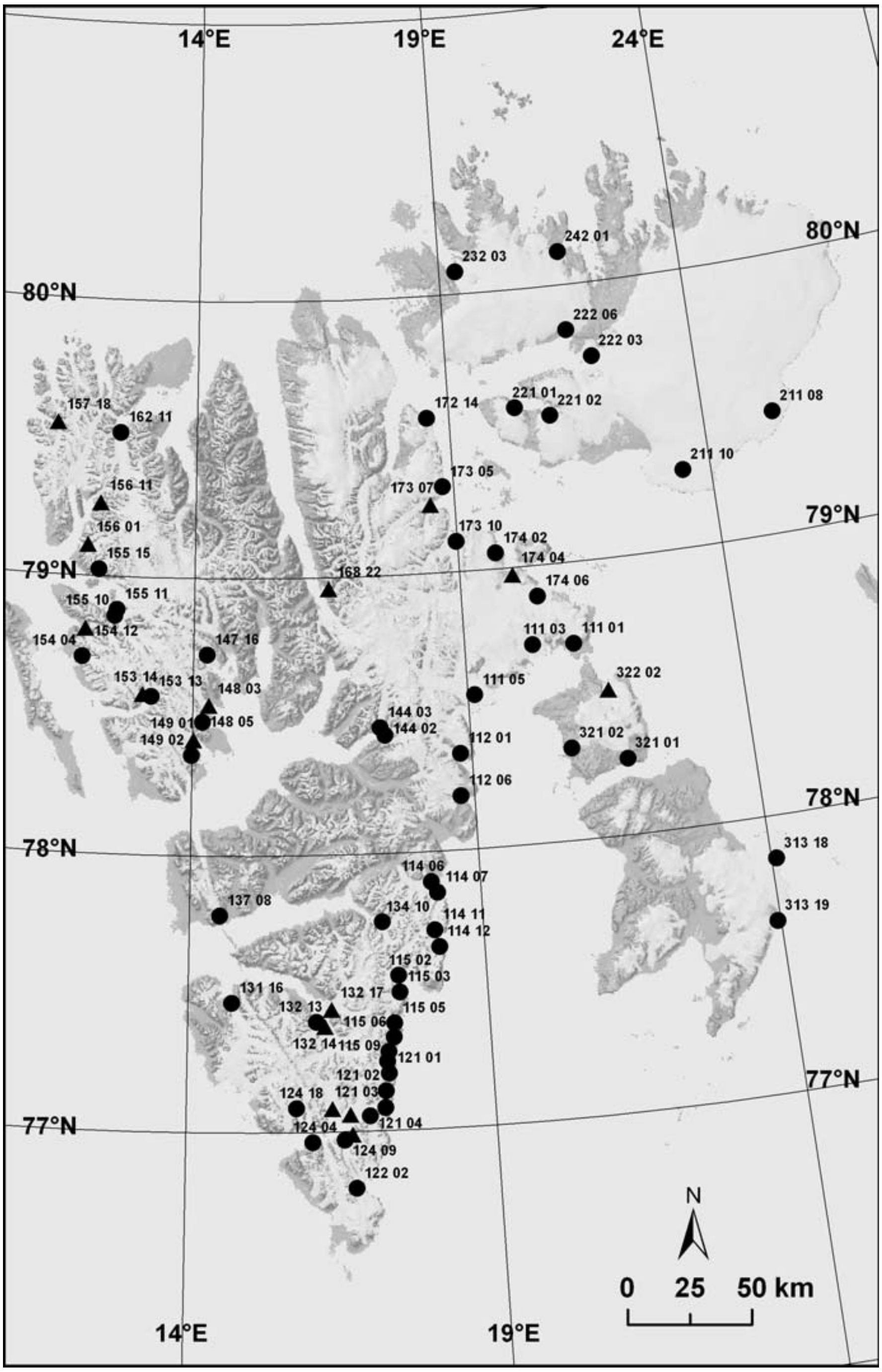

Fig. 9. Distribution of surges of calving glaciers in Svalbard during last 150 years (*cf.* Table 3): glaciers with registered surge (dots) and glaciers with evidence of surge in their morphology (triangles). Glacier numbers as used in the inventory (see Appendix) are indicated.

Table 3

Registered surges of tidewater glaciers in Svalbard (information sources: Jania 1988a, 2006; Lankauf and Wójcik 1987; Lefauconnier and Hagen 1991; Hagen *et al*. 1993; Rolstad *et al*. 1997; Dowdeswell *et al*. 1999; Dowdeswell and Benham 2003; Jania *et al*. 2003; Murray *et al*. 2003a, b; Kääb *et al*. 2006; Nuth *et al*. 2007; Adamek 2007 – personal comunication); No. – glacier number according to the WGI system (*cf.* Appendix – Table I and Figs 12–30), *ca* – circa, b – between, # – glaciers, which were calving in the past, but now terminate on land.

No.	Glacier name	Surge year / period	No.	Glacier name	Surge year / period
111 01	Pedasjenkobreen	b. 1925–35	144 03	Tunabreen	1930, 1970, 2003–?
111 03	Sonklarbreen	*ca* 1910	147 16	Sefströmbreen	1896
111 05	Negribreen	1935–36	148 05	Wahlenbergbreen	1908
112 01	Hayesbreen	1901	149 02	Nansenbreen	1947
112 06	Ulvebreen	b. 1896–1900	153 13	Osbornebreen	1987–90
114 06	Inglefieldbreen	1952	154 04	Aavatsmarkbreen	1982–85
114 07	Arnesenbreen	b. 1925–35	155 10	Kongsvegen	1948
114 11	Richardsbreen	b. 1990–2002	155 11	Kronebreen	1869
114 12	Thomsonbreen	b. 1950–60	155 15	Blomstrandbreen	1960
115 02	Strongbreen	b. 1870–76	162 11	Monacobreen	*ca* 1991–97
115 03	Perseibreen	2000–?	172 14	Odinjokulen N	b. 1965–70
115 05	Jemelianovbreen	1971	173 05	Kosterbreen	*ca* 1930, b. 1956–70
115 06#	Anna Margrethebreen	1970	173 10	Hinlopenbreen	1969–72
115 08	Skimebreen	1970	174 02	Alfarvegen	b. 1970–80
115 09	Davisbreen	*ca* 1960	174 06	Hochstatterbreen	b. 1895–1900
121 01	Crollbreen	b. 1936–61	211 08	nameless	b. 1850–1873, 1992–94
121 02	Markhambreen	b. 1930–36	211 10	Brasvellbreen	1937–38
121 03#	Staupbreen	*ca* 1960	221 01	Glitnefonna Ne	1938
121 04	Hambergbreen	*ca* 1890, *ca* 1960	221 02	Palanderbreen	1969–70
122 02	Vasilievbreen	*ca* 1961	222 03	Etonbreen	1938
124 04	Körberbreen	1938, *ca* 1960	222 06	Bodleybreen	1973–80
124 09	Mendelejevbreen	*ca* 2000	232 03	S Franklinbreen	1956
124 18	Paierlbreen	1993–99	242 01	Rijpbreen	1938, 1992
131 16	Recherchebreen	1838, 1945	313 18	Stonebreen	b. 1936 – 1971, b. 1850–60
132 13	Zawadzkibreen	2006–?	313 19	Kong Johans Bre	b. 1925–1930
134 10#	Bakaninbreen	1985–90	321 01	Freemanbreen	1955–56
137 08	Fridtjovbreen	1861, *ca* 1991–97	321 02	Duckwitzbreen	1918
144 02 #	Von Postbreen	1870, 1980			

Glacier surges are an important element of the dynamics of many Svalbard ice masses. In the active phase of a surge, the ice flow velocity increases by several orders of magnitude. Fast down-glacier transfer of ice is observed, the glacier surface becomes badly crevassed (*cf.* Fig. 10d), and frontal advance is often noted (Meier and Post 1969). After a surge, glaciers may stagnate for periods of decades or even centuries. Thinning of the glacier tongue and frontal retreat have commonly been observed during the quiescent phase of a surge cycle.

The active phase of surging affects the ice flux from tidewater glaciers (*cf.* Table 2) and the calving rate is naturally increased. Based on published data, 55 tidewater glaciers (33% of all tidewater glaciers) have been considered as surge-type (Table 3, Fig. 9). However, a new approach to the evaluation of the number of surge-type glaciers within the population of Svalbard tidewater glaciers has been made in this study. On the basis of publications, unpublished reports, personal communications and interpretations of aerial photographs and satellite images (*e.g.* folded foliation and looped medial moraines visible on glacier surfaces), up to 43% of Svalbard tidewater glaciers could be classified as surge type (Fig. 9). These glaciers were probably actively surging at some time during the 20th century.

Iceberg calving from Svalbard glaciers

The calculation of the volume of ice lost by calving of icebergs from a tidewater glacier is possible when the following quantities are known: (1) the velocity of the glacier averaged over the cross sectional area of the glacier terminus, (2) ice-cliff area, (3) glacier front advance or retreat. It can be described by:

$$Q_C = V \cdot C \cdot H + X \cdot C \cdot H \qquad (1)$$

where: Q_c is the volumetric flux of icebergs, V is the mean ice flow velocity, C is the cliff length, H is the ice thickness and X is front retreat (positive) or advance (negative).

The estimation of iceberg production from the whole Svalbard archipelago requires these data for every tidewater glacier on the archipelago but we have no data of any kind for most glaciers. Therefore, we have tried to approximate the annual rate of ice movement from the pattern and size of the zone of crevasses on each tidewater glacier in Svalbard.

Our classification of tidewater glaciers according to their dynamics is based on the size of the crevassed zone close to the glacier termini. A relationship between glacier velocity and the occurrence of crevasses was used to estimate the dynamics of all tidewater glaciers in Svalbard. This approach is predicted upon a simple assumption: when glacier speed is high, more crevasses are noted in the frontal part of a glacier and the area of crevassing is larger (*i.e.* a fast glacier produces a larger crevasse system near its front).

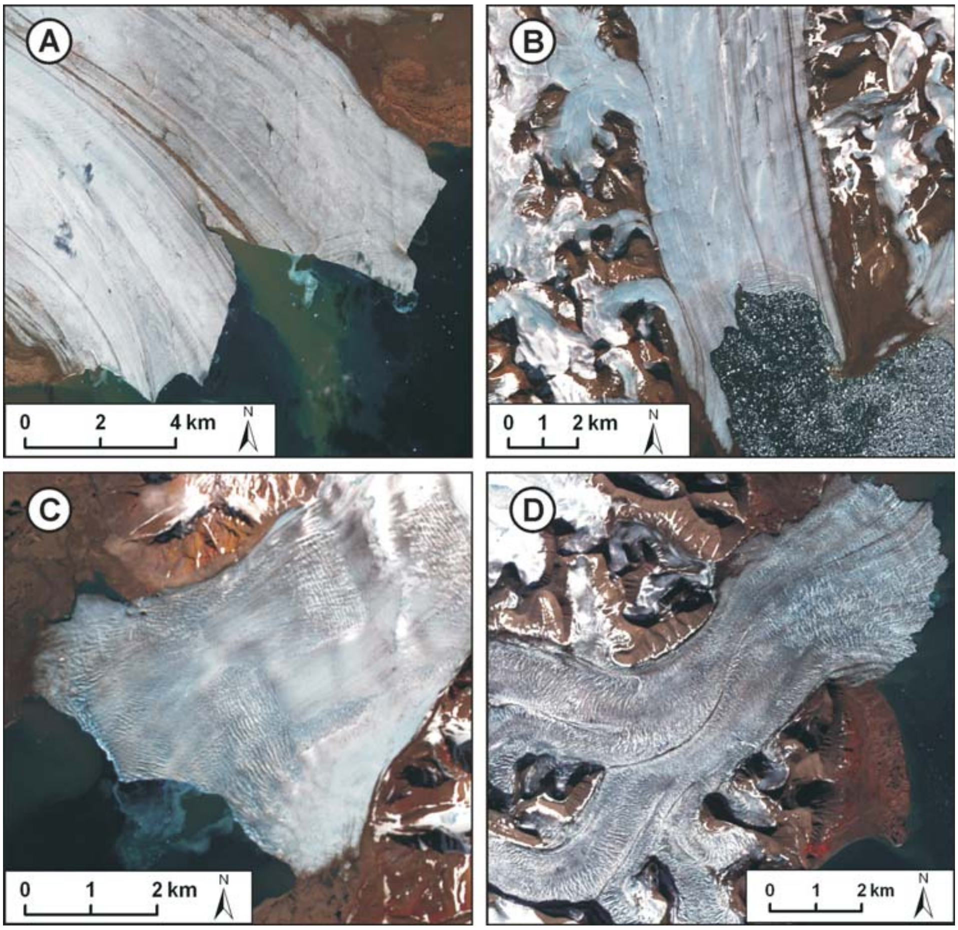

Fig. 10. Examples of ASTER geocoded images (321 bands) of glaciers classified into different groups of flow dynamics: a) Negribreen – very slow or stagnant glacier (5.08.2003); b) Storbreen – slow-flowing glacier (7.08.2004); c) Austre Torellbreen – fast-flowing glacier (23.07.2005); d) Perseibreen – active surge glacier (7.08.2004).

Crevasses on tidewater glaciers are generally parallel or semi-parallel to the ice-cliff and their origin is related to the increase of tensile stresses in the lower reaches of the glacier (*cf*. Van der Veen 1999), as longitudinal gradient in flow velocity rises when the ice approaches the glacier terminus. Although undulations in the underlying bedrock surface may influence the size and pattern of a crevasse field to some extent, flow velocity is assumed to be the primary influence. In active phase of a surge cycle, a substantial part of glacier is usually heavily crevassed (*cf.* Fig. 10d).

As linear features, crevasses are easily identified on the surface of glaciers registered on Terra-ASTER satellite images (even when their width is less than 15 m). It is possible to define the distribution and patterns of crevasses semi-automatically using the remote sensing texture analysis (*MaZda*, *cf.* Fig. 4b) and GIS software (*e-Cognition*, *ArcGIS*) supported by manual digitization of crevassed areas.

Data on the near terminus velocity of different types of glaciers were required for classification of glaciers according to their dynamics. Flow velocity measurements for 46 glaciers were obtained (Table 2). From these measurements made over the last two decades we used velocity data from only 33 glaciers. Analysis of the dynamic status of tidewater glaciers was based on several characteristics: length of glacier, length of crevassed zone, area of glacier, area of crevassed zone and length of cliff, as acquired from satellite imagery. Owing to the difficulties with determining of crevasses zone due to snow cover on glacier front, some of the velocity information was rejected. 16 apparently stagnant glaciers that currently have very small crevassed areas and no discernible motion (*cf.* Table 2) fall into first category of "very slow or stagnant glaciers". The morphometric features of a further 17 glaciers were compared with their mean annual flow velocity (Table 4).

The highest correlation coefficient ($r = 0.71$) was found between 17 glacier velocities and the length and area of crevassed zones. In practice, it is easier to measure the linear extent of the crevassed zone upstream from the ice-cliff along the centerline than to measure its area. A multiple regression with use of both parameters, length and area of crevassed zones, was also calculated, but correlation coefficient of regression equation was too low ($r = 0.56$). Therefore parameter "length of the crevassed zone" was used for further velocity and calving flux assessments. In order to estimate the velocities of all the tidewater glaciers in the archipelago, the glaciers were classified into four groups with different dynamics (Table 5): (1) very slow or stagnant glaciers with velocities (Vg) in the range 10 ± 5 m yr^{-1} and length of crevassed zone (Lc) of 0–300 m, (2) slow-flowing glaciers with Vg of 70 ± 30 m yr^{-1} and Lc of 300–1000 m, (3) fast-flowing glaciers with Vg of 200 ± 50 m yr^{-1} and Lc of ≥ 1000 m, (4) surging glaciers (in the active phase) and fast ice streams with Vg > *ca* 700 m yr^{-1} and Lc of a few kilometers. Ranges (estimated errors) in velocities in individual groups are assumed on the basis of sparse data on glacier motion. Examples of the different dynamic categories of glaciers are presented in Fig. 10.

Every tidewater glacier on Svalbard was assigned to one of the above groups and an average velocity for a given dynamic type was applied to all glaciers of that type. Special attention was paid to those glaciers that have recently surged. Their surfaces are heavily crevassed but they are slow moving or even stagnant. Thus, every glacier with traces of a surge on its surface was examined individually by applying the feature tracking method to ASTER images from different years to determine its velocity. Other sources of data (publications, unpublished information) were also used for this purpose.

The classification presented allowed us to approximate the average flow velocity of every tidewater glacier in the archipelago on the basis of length of the crevassed zone. As a result of classification, very slow or stagnant glaciers constitute 49% of Svalbard tidewater glaciers, while slow glaciers make up 30% of the

Table 4

Correlation coefficients between velocity of glaciers (Vg) and their morphometric parameters. WGI No. – glacier number in the World Glacier Inventory, Lg – glacier length along the centerline, Lc – length of crevassed zone on the centerline, Ag – area of glacier, Ac – area of crevassed zone, α – glacier slope, Vg – glacier velocity near terminus (from field survey and by remote sensing methods extracted from different sources). Correlation coefficients indicated in bold are statistically essential; $p = 0.05$.

WGI No.	Glacier name	Lg	Lc	Lc/Lg	Ag	Ac	Ac/Ag	α	Vg
		m	m	%	km^2	km^2	%	°	m yr^{-1}
154 04	Aavatsmarkbreen	14800	600	4.1	68.0	1.48	2.2	2.7	40
154 12	Comfortlessbreen	12800	350	2.7	41.7	0.50	1.2	3.7	55
153 16	Gaffelbreen	6800	600	8.8	17.0	0.53	3.1	5.4	70
124 12	Storbreen	22100	800	3.6	161.8	3.42	2.1	1.5	80
252 02	Nilsenbreen	43000	500	1.2	263.6	0.20	0.1	0.9	84
124 08	Chomjakovbreen	7200	350	4.9	12.1	0.39	3.2	4.0	85
124 04	Körberbreen	5300	400	7.5	7.8	0.31	3.9	7.9	90
124 07	Samarinbreen	9200	1000	10.9	60.8	2.98	4.9	5.7	115
222 08	Aldousbreen	21000	1400	6.7	126.0	5.28	4.2	1.6	120
125 05	V. Torelbreen	28700	700	2.4	182.9	2.31	1.3	1.3	140
124 20	Hansbreen	15600	1400	9.0	53.0	2.17	4.1	1.9	150
124 17	Mülbacherbreen	15700	3000	19.1	50.2	5.82	11.6	2.3	210
222 10	Idunbreen	25400	2000	7.9	323.2	5.57	1.7	1.3	230
153 19	Dahlbreen	18800	1300	6.9	110.4	3.10	2.8	2.7	250
153 13	Osbornebreen	20000	1500	7.5	130.6	2.62	2.0	2.6	250
125 03	Au Toreellbreen	20800	2000	9.6	136.2	6.04	4.4	2.0	260
222 09	Frazerbreen	22500	1300	5.8	220.9	5.01	2.3	1.5	307
r – correlation with Vg		0.25	**0.71**	0.39	0.43	**0.71**	0.20	-0.4	–

Table 5

Categories of front types of Svalbard tidewater glaciers according to their dynamics.

Types of tidewater glaciers fronts	Length of crevassing zone [m]	Glacier velocity [m yr^{-1}]	Number of glaciers
(1) very slow or stagnant glaciers	0–300	10 ± 5	72
(2) slow-flowing glaciers	≥300–1000	70 ± 30	69
(3) fast-flowing glaciers	≥1000	200 ± 50	37
(4) surging glaciers and fast ice streams	>1000	700	3

whole tidewater glacier population, and fast glaciers make up 19%. Only 2% of all tidewater glaciers were surging during the 2000–2006 study period.

Data on the cross-sectional area of the calving termini of glaciers are essential for the calculation of ice discharge into the sea. Such data are not available for the majority of Svalbard tidewater glaciers. Therefore, estimates of the cross sectional areas of all calving tongues were based on measurements of the lengths of

Table 6

The length of ice cliffs on the main islands of Svalbard: L_1 – Dowdeswell (1989); L_2 – from ASTER satellite images.

Island	Length of ice cliffs	
	L_1 [km]	L_2 [km]
Spitsbergen	484	388.4
Nordaustlandet	306	272.3
Edgeøya	79	68.7
Prins Karls Forland	17	8.9
Barentsøya	23	8.8
Storøya	13	12
Kvitøya	106	100
Sum	**1028 km**	**859.1 km**

Table 7

The calving losses from different types of glacier (without taking into the consideration recession of termini); Qc – mean annual calving flux; ΔQc – sum of calving estimation errors with assumption of a stable front position.

Types of tidewater glaciers	Qc [km^3 yr^{-1}]	ΔQc [km^3 yr^{-1}]
(1) very slow or stagnant glaciers	0.4	0.2
(2) slow-flowing glaciers	1.8	0.8
(3) fast-flowing glaciers	2	0.5
(4) surging glaciers and fast ice streams	1	–
Total for Svalbard	**5.2**	**1.5**

ice-cliffs and assumptions about the mean thickness of glaciers in contact with sea water. The length of all tidewater glacier cliffs was measured using geocoded ASTER images (Table 6). This amounts to 860 km, a figure which is 16% shorter than that proposed by Dowdeswell (1989) – 1028 km. This may simply reflect reduction of seaward margins of tidewater glaciers in around last 40 years.

The average ice thickness near the terminus was estimated from airborne and ground-based radio echo soundings of some dozens of glaciers and from the very sparse data on ocean depth close to the present ice front positions (Dowdeswell *et al*. 1984; Drewry and Liestøl 1985; Hagen *et al*. 2003a). From this data average thickness of glacier fronts in the archipelago is estimated to be about 100 m ± 10 m.

An extensive analysis of images has enabled us to obtain other data necessary to estimate the annual calving flux of ice from Svalbard glaciers to the ocean in the first years of the 21st century. The calving loss from glaciers with stable ice front positions was estimated to be about 5.2 km^3 yr^{-1} ± 1.5 km^3 yr^{-1} (Table 7).

Terminus position changes of about 30 tidewater glaciers were measured and, for the purposes of calculation of the calving flux, an average retreat rate by

30 m yr^{-1} was assigned to the whole population. Taking into account the mean recession rate of all the tidewater glaciers, the total length of ice-cliffs (860 km) and the average thickness of glaciers at the terminus (100 m), the additional calving ice flux as a result of glacier retreat was estimated to be 2.28 km^3 yr^{-1}. The total calving flux from Svalbard glaciers (excluding Kvitøya) was estimated to be 7.5 km^3 yr^{-1}.

Overall uncertainty on the calving flux is derived assuming: average ice thickness of 100 m ± 10 m, mean ice flow velocity and error of velocity according to Table 5, the average front retreat of 30 m yr^{-1} ± 10 m yr^{-1}, the cliff length from Table I (Appendix) and error of the cliff length of ±15 m. These quantities are the best possible values based on our observations. Sum of individual errors of calving flux of all glaciers amounts to 1.9 km^3 yr^{-1}.

Thus, the total calving flux from Svalbard glaciers was estimated to be in the range 5.6–9.4 km^3 yr^{-1} of ice (5.0–8.4 km^3 yr^{-1} water equivalent – w.e.) with the best estimate of 7.5 ± 1.9 km^3 yr^{-1} (6.75 ± 1.7 km^3 yr^{-1} w.e.).

Discussion and conclusions

The present analysis of tidewater glaciers in Svalbard is based on examination of ASTER satellite images from the period 2000–2006, while data in Hagen's *et al.* (1993) inventory were collected from sources of different origin and age. Recent data have shown that there are 163 tidewater glaciers in Svalbard. Compared to the previous inventory, 14 glaciers have retreated from the sea to land during the last 30–40 years, and 11 formerly land-based glaciers are now in contact with the sea.

In this inventory, tidewater glaciers were classified into four groups on the basis of their dynamic state and frontal crevasse patterns: (1) very slow or stagnant glaciers, (2) slow-flowing glaciers, (3) fast-flowing glaciers, (4) surging glaciers (in the active phase) and fast ice streams.

Our estimates of total mass loss due to calving from Svalbard glaciers (excluding Kvitøya) yield values of 5.0–8.4 km^3 yr^{-1} (w.e.) with the best estimate being 6.75 ± 1.7 km^3 yr^{-1} (w.e.), which is substantially more than the calving flux of 4 ± 1 km^3 yr^{-1} (w.e.) given by Hagen *et al.* (2003a) and significantly less than the value estimated by Lefauconnier *et al.* (1993), 7.44–9.94 km^3 yr^{-1}.

The differences between these estimates stem from assuming general velocity for the whole archipelago. Hagen *et al.* (2003a) estimated the average velocity of calving fronts through the archipelago at 20–40 m yr^{-1}, and general retreat of glacier fronts at 10 m yr^{-1}. Lefauconnier *et al.* (1993) calculated linear calving (flow velocity plus retreat of the front) on 75 m per year for Spitsbergen and 100 meters per year for the islands of the eastern Svalbard. Therefore, Hagen *et al.* (2003a) result is smaller because they assumed too low velocity for all Svalbard glaciers. Results of Lefauconnier *et al.* (1993) are giving too high values, because they estimated the calving flux by averaging velocities of few glaciers larger and faster than the majority of their population.

The total surface runoff from Svalbard glaciers due to melting of snow and ice was estimated by Hagen *et al*. (2003a) as roughly 25 ± 5 $km^3 yr^{-1}$, which corresponds to a specific runoff of 680 ± 140 mm yr^{-1}. This is only slightly more than the annual snow accumulation. Taking this value into account and knowing the area of the tidewater glaciers studied (21210 km^2), the total amount of meltwater discharged from them can be estimated as 14.5 ± 3 $km^3 yr^{-1}$ (w. e.). Thus, the mass loss by calving from these glaciers is on the order of 47% of the surface melting and constitutes *ca* 32% of the total mass loss from all the Svalbard tidewater glaciers. Comparison of total melting (25 ± 5 $km^3 yr^{-1}$) from Svalbard glaciers with our estimates of mass loss due to calving suggests that calving contributes *ca* 17–25%, with a mean value of 21% (compared to 16% in Hagen *et al*. 2003a) to the overall mass loss from Svalbard glaciers, which is a significant component of the overall mass balance.

Our calculations of ice flux are sensitive to the assumed average retreat rate for all glaciers. Comparison of results shows that the calving flux stemming from a rate of glacier retreat on the order of 30 m yr^{-1} would be 2.3 $km^3 yr^{-1}$, or 30% of the total calving flux from the archipelago. By comparison, for an ice front retreat of 40 m yr^{-1} the calving flux would be 3 $km^3 yr^{-1}$, or 37% of the total calving flux. To give better estimate of the calving flux, there is a need for some more accurate data on ice thickness and front retreat for the whole archipelago. There is also need for more data on ice velocity to improve classification and decrease errors of calculated calving flux.

The length of all tidewater glacier cliffs is 860 km, a figure that is 16% less than that proposed by Dowdeswell (1989) – 1028 km. One can expect further length reductions due to the continued recession of glacier fronts.

We are fairly certain that about 33% of all tidewater glaciers (54 in number) are of surge-type, but indirect evidence of past surges (*e.g.* folded medial moraines, looped foliation and frontal push moraines) found on ASTER images suggest that this percentage may actually be larger (40–45%).

According to Jania and Hagen (1996), the velocities of glaciers of Severnaya Zemlya and Novaya Zemlya vary between 10–150 m yr^{-1}. A few glaciers in Franz Josef Land and northern Novaya Zemlya have velocities highier than 160 m yr^{-1} (Sharov 2005). The Academy of Sciences Ice Cap, the largest in the Russian Arctic, has four fast flowing outlets with lateral shear zones and a maximum velocity of 140 m yr^{-1} (Dowdeswell *et al*. 2002). In Svalbard the flow of several glaciers is faster than 200 m yr^{-1}, suggesting that they flow appreciably faster than glaciers in other parts of the Eurasian Arctic. This is probably related to the higher mass turnover in the warmer, wetter climate of Svalbard.

Estimated calving fluxes for Arctic are shown in Table 8. Some data are somewhat out-of-date and there is not data for the whole Canadian Arctic. However, despite the lack of a complete error assessment we may conclude that losses by calving from Svalbard appear to be the highest in the Eurasian Arctic.

Table 8

Estimations of volume of ice lost by calving in Eurasian and North Atlantic Arctic area (data sources: [1] Błaszczyk 2008, [2] Govorukha 1989, [3] Abramov 1996, [4] Dowdeswell *et al*. 2002, [5] Rignot and Kanagaratnam 2006, [6] Burgess *et al.* 2005, [7] Willamson *et al.* 2008, [8] Short and Gray 2005, [9] http://nsidc.org/data/docs/noaa/g01130_glacier_inventory/).

Island	Calving flux [km^3 yr^{-1}]	Glaciers area [km^2]	Annual specific mass balance attributable to iceberg calving [m yr^{-1}]
Svalbard[1]	7.5	36 600	0.20
Novaya Zemlya[2]	2	23 600	0.087
Franz Josef Land[3]	2.26	13 700	0.16
Academy of Sciences Ice Cap (Severnaya Zemlya)[4]	0.65	5 500	0.12
Greenland[5]	150	1 640 000	0.09
Devon Ice Cap (Devon Island)[6]	0.53	14 000	0.04
Agassiz Ice Cap[7]	0.67 ± 0.15	19 500	0.03
Otto Glacier[7]	0.26 ± 0.13	2 000	0.13
Prince of Wales Icefield[8] (Ellesmere Island)	2.81 ± 0.69	1 370[9]	2.05

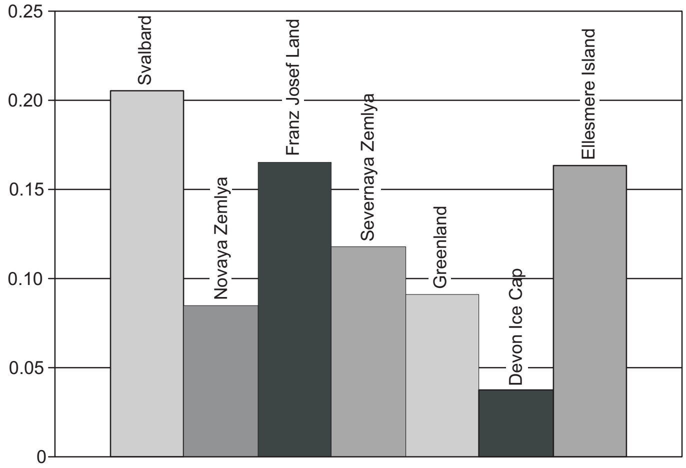

Fig. 11. Annual specific mass balance attributable to the calving flux (calving flux/area) [m yr^{-1}].

The contribution of Svalbard iceberg flux to sea-level rise may be as much as 0.02 mm yr^{-1} and it is certainly greater than the value of 0.01 mm yr^{-1} presented by Hagen *et al*. (2003a). Although it is a small part of the total sea-level rise from glaciers and ice caps (estimated at 1.1 mm yr^{-1}; Meier *et al*. 2007) and minuscule compared with the contributions of Greenland to sea-level rise (0.5 mm yr^{-1}; Rignot and Kanagaratnam 2006), the annual specific mass loss due to calving from the Svalbard Archipelago appears to be the largest in the Arctic (Fig. 11). One may reasonably predict that some present-day tidewater glaciers will retreat to the land

and that the lengths of the remaining ice cliffs will be reduced. Therefore, in the coming decades, a decrease in the calving flux may be expected.

In conclusion, we suggest that area and pattern of crevasses near tidewater glacier termini seems to be a simple and reliable indicator of the dynamics of these glaciers. It also enables the estimation of the likely flow velocity and calving flux of individual glaciers in Svalbard.

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Appendix

Svalbard tidewater glaciers inventory

Table I

Inventory of tidewater glaciers of Svalbard. List of glaciers in regions of archipelago according to Hagen *et al*. (1993). Compare with the corresponding general location map (Fig. 12) and maps of regions (Figs 13–30).

Ident The identification number for each ice stream (according to World Glacier Inventory). The first digit gives the region, the second the major drainage basin, the third the secondary drainage basin, and the fourth and fifth give the ice stream.

Glacier name The name of the glacier unit, if it has one.

Region Regions of Svalbard distinguished by Hagen *et al*. (1993).

Image Nb Numbers of ASTER and LANDSAT 7 images (according to Table 1); * – GISICE – Glaciological Database of the Eurasian High Arctic; CD-ROM (Dowdeswell *et al.* 2001).

Lg Length of glacier.

Ag Area of glacier.

Ac Area of crevassed zone.

Ice cliff Length of cliff.

Lc Length of crevassed zone.

R_1 Average ice-cliff position change (area of glacier retreat/advance divided by the length of the ice cliff); positive values for advance, negative values for retreat.

R_2 Ice-cliff position change (measured along center-line); positive values for advance, negative values for retreat.

Front position change (years) and source Source and year of ice front change measurements.

Ft Front type of Svalbard tidewater glaciers: (1) very slow or stagnant glaciers, (2) slow-flowing glaciers, (3) fast-flowing glaciers, (4) surging glaciers (in the active phase) and fast ice streams.

Qc Estimated calving intensity.

N 4W1 SPITSBERGEN

Region 11 – SPITSBERGEN SE

Ident	Glacier name	Region	Image Nb	Lg [m]	Ag [km²]	Ac [km²]	Ice-cliff [m]	Lc [m]	R_1 [m]	R_2 [m]	Front position change (years) and source	Ft	Qc [km³ yr⁻¹]
111 01	Pedasjenkobreen	11	7, 6	6700	36.2	0	2350	0		0	ASTER, 2003–2005	1	0.0024
111 03	Sonklarbreen	11	7	13500	207.2	0	17060	0				1	0.0171
111 05	Negribreen	11	7	51000	916.2	0.51	21240	200	-73	-50	ASTER, 2003–2005	1	0.0212
111 06	Johansenbreen	11	7	10500	39.8	0	1030	0		0	ASTER, 2003–2005	1	0.0010
	Petermannbreen	11	16, 7, 20, 41	19200	114.8	1.45	3390	600	-22	-40	ASTER, 2003–2005	2	0.0238
112 01	Hayesbreen	11	16, 41	21000	119.7	1.37	3950	400				2	0.0277
112 06	Ulvebreen	11	16	15400	54.7	0.15	1960	180				1	0.0020
114 05	Nordsysselbreen	11	17	18820	45.9	0	420	0				1	0.0004
114 06	Inglefieldbreen	11	17	20170	59.3	0	4620	0				1	0.0046
114 07	Arnesenbreen	11	17	11820	21.0	1.63	2300	1100				3	0.0460
114 08	Beresnikovbreen	11	17	8200	23.2	0	1760	0				1	0.0018
114 11	Richardsbreen	11	23, 17	12200	55.1	32.19	2150	1220				1	0.0022
114 12	Thomsonbreen 1	11	23	6900	19.5	0	1200	0				1	0.0014
	Thomsonbreen 2	11	23	9200	18.9	0.15	1360	280				1	0.0012
115 01	Kvalbreen	11	1	15000	62.0	0.97	3670	300	-67	-85	ASTER, 2002–2004	2	0.0257
115 02	Strongbreen	11	17, 23	15500	49.7	0.06	3850	80	-36	-43	ASTER, 2002–2005	1	0.0038
	Morsjnevbreen	11	17, 23	20200	92.3	0.16	4820	200	-41	-67	ASTER, 2002–2005	1	0.0048
115 03	Perseibreen	11	23, 1	15000	57.3	57.31	6930	7000	+700		ASTER, 2002–2004	4	0.4848
115 05	Jemelianovbreen	11	1, 5	15400	39.8	0	2230	0	-115	-100	ASTER, 2002–2004	1	0.0022
	Kvastbreen	11	23	9800	8.6	0	410	0				1	0.0004
115 08	Skimebreen	11	23	6550	8.5	0	1420	0		0	ASTER, 2002–2004	1	0.0014
115 09	Davisbreen	11	9	8900	33.9	2.07	3550	900	-48	-60	ASTER, 2002–2004	2	0.0249

Region 12 – SPITSBERGEN S

Ident	Glacier name	Region	Image Nb	Lg [m]	Ag [km²]	Ac [km²]	Ice-cliff [m]	Lc [m]	R_1 [m]	R_2 [m]	Front position change (years) and source	Ft	Qc [km³ yr⁻¹]
121 01	Crollbreen	12	9	7700	16.4	0.31	2340	250				1	0.0023
121 02	Markhambreen	12	9	8500	46.3	1.18	2080	650	-46	-50	ASTER, 2002–2004	2	0.0145
121 04	Sykorabreen	12	9	12480	57.0	1.60	1890	1000				3	0.0378
	Hambergbreen	12	9	4000	34.4	4.90	2710	1700				3	0.0542
122 02	Vasilievbreen1	12	9	12400	116.4	1.78	8940	280				1	0.0089
	Vasilievbreen2	12	9	9100	32.3	1.13	5610	400				2	0.0393
	Vasilievbreen3	12	9	8700	18.1	0.47	3660	280				1	0.0037
123 03	Olsokbreen	12	9, 11	16600	100.2	1.63	4970	700				2	0.0348
124 04	Körberbreen	12	9	5300	7.8	0.31	1060	400				2	0.0074
124 05	Petersbreen	12	9	2280	1.1	0.03	340	100				1	0.0003
124 07	Samarinbreen	12	9	9200	60.8	2.98	3180	1000				3	0.0636
124 08	Chomjakovbreen	12	9	7200	12.1	0.39	1070	350				2	0.0075
124 09	Mendelejevbreen	12	9	10500	29.4	29.39	1820	1050				1	0.0018
124 10	Svalisbreen	12	9	11000	30.2	2.83	3020	1600				3	0.0604
124 11	Hornbreen	12	9	26230	138.7	2.65	3880	600				2	0.0271
124 12	Storbreen	12	9	22100	161.8	3.42	7690	800				2	0.0538
124 13	Hyrnerbreen	12	9	2500	4.1	0.03	920	60				1	0.0009
124 15	Wibebreen	12	9	4300	4.6	0	590	0				1	0.0006
124 16	Kvalfangarbreen	12	9	5200	12.5	0.22	1120	250				1	0.0011
124 17	Mühlbacherbreen	12	9	15700	50.2	5.83	1620	3000				3	0.0324
124 18	Paierlbreen	12	9, 10	22000	92.6	1.33	1610	2000	-106	-135	ASTER, 2004–2006	3	0.0321
124 20	Hansbreen	12	9, 10	15600	53.0	2.17	1900	1400	-40		Jania (2006), 1989–2000	3	0.0381
125 03	Au Torellbreen	12	10	20800	136.2	6.04	5280	2000	-75	-120	ASTER, 2005–2006	3	0.1056
125 05	Ve Torelbreen	12	10	28700	182.9	2.31	4790	700		+80	ASTER, 2005–2006	2	0.0335

Region 13 – BELLSUND

Ident	Glacier name	Region	Image Nb	Lg [m]	Ag [km^2]	Ac [km^2]	Ice-cliff [m]	Lc [m]	R_1 [m]	R_2 [m]	Front position change (years) and source	Ft	Qc [km^3 yr^{-1}]
131 16	Recherchebreen	13	10	22800	120.2	0	2110	0	-71	-50	ASTER, 2005–2006	1	0.0021
132 13	Zawadzkibreen	13	10	20000	83.1	0	1710	0		0	ASTER, 2005–2006	1	0.0017
132 14	Nathorstbreen	13	10, 9, 5, 1	25000	318.8	1.70	6230	1600		-77	Carlsen *et al.* (2003) 1976–2002	2	0.0436
132 17	Liestolbreen	13	1	22800	99.0	0.64	4700	250				1	0.0047
132 18	Doktorbreen	13	1, 17, 10	28700	95.0	0	190	0				1	0.0002
134 09	Paulabreen	13	17	17000	56.4	0	1030	0				1	0.0010
137 08	Fridtjovbreen	13	15	14100	39.8	0.30	2410	300				2	0.0169

Region 14 – ISFJORDEN

Ident	Glacier name	Region	Image Nb	Lg [m]	Ag [km^2]	Ac [km^2]	Ice-cliff [m]	Lc [m]	R_1 [m]	R_2 [m]	Front position change (years) and source	Ft	Qc [km^3 yr^{-1}]
144 03	Tunabreen	14	19, 20	25200	137.6	46.84	3490	1740	+229		L, ASTER,1999–2004	4	0.2440
145 06	Nordenskiöldbreen	14	20, 19	13600	24.8	0.45	420	1000				3	0.0085
	Nordenskiöldbreen	14	20, 19	22300	144.7	7.48	3650	1500				3	0.0729
147 16	Sefströmbreen	14	12	19000	117.5	0.59	6400	350				1	0.0064
148 03	Sveabreen	14	12	29330	156.6	7.06	4150	2200				3	0.0830
148 05	Wahlenbergbreen	14	21, 12	26700	104.2	0.75	1610	400				2	0.0113
149 01	Borebreen	14	21, 13, 12	20100	87.0	0.13	5130	150	-45	-67	ASTER, 2001–2004	1	0.0051
149 02	Nansenbreen	14	21	11700	31.1	0.42	2830	150	-32	-50	ASTER, 2001–2004	1	0.0028
149 03	Esmarkbreen	14	21	12100	33.4	0.16	3630	240				1	0.0036

Region 15 – SPITSBERGEN NW

Ident	Glacier name	Region	Image Nb	Lg [m]	Ag [km²]	Ac [km²]	Ice-cliff [m]	Lc [m]	R_1 [m]	R_2 [m]	Front position change (years) and source	Ft	Qc [km³ yr⁻¹]
151 07	So Buchananisen	15	26	3100	14.2	0.23	4300	220				1	0.0043
151 08	No Buchananisen1	15	26	3800	5.7	0.77	1350	500				2	0.0094
	No Buchananisen2	15	26	2300	2.6	0.12	720	230				1	0.0007
151 10	Murraybreen	15	26	5000	9.1	0	2570	0				1	0.0026
153 12	Vintervegen	15	12, 13	11500	30.7	0.10	760	150	-47	-33	ASTER, 2000–2006	1	0.0008
153 13	Osbornebreen	15	12, 13	20000	130.6	2.62	2390	1500	-73	-110	ASTER, 2000–2006	3	0.0478
153 14	Konowbreen	15	12, 13	11500	39.9	0.51	1550	450	-55	-67	ASTER, 2000–2006	2	0.0108
153 16	Gaffelbreen	15	13	6800	17.0	0.53	1200	600	-27	-33	ASTER, 2000–2006	2	0.0084
153 19	Dahlbreen	15	12, 13	18800	110.4	3.10	2980	1300	-16	-30	ASTER, 2000–2006	3	0.0595
154 04	Aavatsmarkbreen	15	13	14800	68.0	1.48	3680	600	-50	-75	ASTER, 2000–2006	2	0.0258
154 12	Comfortlessbreen	15	12, 13	12800	41.7	0.50	2390	350		0	ASTER, 2000–2006	2	0.0167
155 10	Kongsvegen	15	12	25500	153.9	0	400	0				1	0.0004
155 11	Kronebreen1	15	12, GISICE*	44700	406.9	37.20	3210	1250				4	0.2247
	Kronebreen2	15	12, GISICE	39000	302.9	14.88	4280	5000				3	0.0856
155 12	Conwaybreen	15	12, 43, 14	15720	34.5	1.58	1450	1250				3	0.0290
155 15	Blomstrandbreen	15	14, 43	17500	65.7	1.35	1950	900				2	0.0137
156 01	Fjortende Julibreen	15	14	16200	52.5	2.62	1840	1400				3	0.0368
156 07	Tinayrebreen	15	14	11700	42.3	9.48	640	7500				3	0.0128
156 11	Mayerbreen	15	14	11900	34.6	1.11	950	1200				3	0.0189
156 12	Kollerbreen	15	14	9620	20.5	0.66	1720	450				2	0.0121
156 14	Lilliehöökbreen 1	15	14	10300	40.1	1.63	3460	450				2	0.0242
	Lilliehöökbreen 2	15	14	20740	142.8	4.68	3970	1100				3	0.0794
	Lilliehöökbreen 3	15	14	13350	28.9	0.55	2410	250				1	0.0024
156 15	Forbesbreen	15	14	5000	9.0	0.32	1060	200				1	0.0011
157 05	Andrebreen	15	14	6720	11.4	0.31	1410	300				2	0.0099
157 06	Tredjebreen	15	14	9000	20.2	0.24	1090	200				1	0.0011
157 08	Femtebreen	15	14	3950	4.4	0	720	0				1	0.0007
157 09	Sjettebreen	15	14	12100	56.4	1.98	4640	600				2	0.0325

157 10	Munthebreen	15	14	3050	2.7	0	380	0				1	0.0004
157 11	Sjubreen	15	14	4680	5.3	0.38	900	500				2	0.0063
157 16	Gullybreen 1	15	14, 43	1720	1.5	0	710	0				1	0.0007
	Gullybreen 2	15	14	4440	7.3	0.48	950	450				2	0.0066
157 18	Waggonwaybreen	15	14	10000	29.1	5.07	1110	4300				3	0.0222
158 01	Kvasspiggbreen	15	43	2400	2.1	0	830	0				1	0.0008
158 02	Scheibreen	15	43	5300	8.1	0	1170	0				1	0.0012
158 04	Smeerenburgbreen 1	15	43, 14	16000	90.7	1.92	3600	800				2	0.0252
	Smeerenburgbreen 2	15	43, 14	5000	4.3	0	630	0				1	0.0006
158 06	Marstranbreen	15	43, 22	1000	4.3	0	600	0				1	0.0006
158 09	Sellströmbreen	15	22	5200	8.1	0.43	1060	480				2	0.0074
158 10	Frambreen	15	22	3700	4.7	0.19	920	200				1	0.0009
158 11	Kennedybreen	15	22	3700	6.2	0.54	1440	500				2	0.0101
158 12	Svitjodbreen	15	22	12200	40.8	1.40	2820	700				2	0.0197
158 14	Holmiabreen	15	22	2200	2.0	0	630	0				1	0.0006

Region 16 – WOOD/WIJDEFJORDEN

Ident	Glacier name	Region	Image Nb	Lg [m]	Ag [km²]	Ac [km²]	Ice-cliff [m]	Lc [m]	R_1 [m]	R_2 [m]	Front position change (years) and source	Ft	Qc [km³ yr⁻¹]
161 02	Hamiltonbreen 1	16	22	1850	1.8	0	550	0				1	0.0005
	Hamiltonbreen 2	16	22	5300	8.1	0.47	580	600				2	0.0041
	Hamiltonbreen 3	16	22	2200	1.5	0.07	340	180				1	0.0003
	Hamiltonbreen 4	16	22	1330	0.4	0	130	0				1	0.0001
161 03	Arneliusbreen	16	22	2300	2.1	0	380	0				1	0.0004
161 04	Smithbreen	16	22	4500	11.5	0.33	2040	350				2	0.0143
161 05	nameless	16	22	3300	2.7	0	510	0				1	0.0005
161 07	Tindebreen	16	22	3150	1.5	0	500	0				1	0.0005
161 08	Sklia	16	22	3150	3.4	0.25	730	400				2	0.0051
161 10	Chauveaubreen	16	14, 22	6200	8.7	0.66	1910	620				2	0.0134
161 11	Raudfjordbreen	16	22, 14	16700	53.8	1.35	1980	700				2	0.0139
162 07	Idabreen	16	14, 22	3200	6.3	1.18	1690	650				2	0.0118

162 08	Emmabreen	16	14, 22	6050	5.6	0.12	640	200				1	0.0006
162 10	Seligerbreen	16	14	8700	34.1	6.55	1800	3500				3	0.0360
162 11	Monacobreen	16	14, 22	40170	344.5	4.13	4540	1500				3	0.0907
168 20	Mittag-Lefflerbreen	16	19, 20	27700	168.4	1.40	3150	500				2	0.0221
168 22	Stubendorffbreen	16	19	22200	29.0	0	1820	0				1	0.0018
169 07	Midtbreen	16	3, GISICE	17000	60.7	0.94	1060	700				2	0.0074
169 09	Nordbreen	16	3, GISICE	15600	86.6	2.38	1790	1300				3	0.0357

Region 17 – SPITSBEREGN NE

Ident	Glacier name	Region	Image Nb	Lg [m]	Ag [km²]	Ac [km²]	Ice-cliff [m]	Lc [m]	R_1 [m]	R_2 [m]	Front position change (years) and source	Ft	Qc [km³ yr⁻¹]
171 05	Valhalfonna	17	4, GISICE	15500	261.1	0	24790	0				1	0.0248
172 08	Kantbreen	17	4, GISICE	25000	185.2	0.13	1650	250				1	0.0016
172 14	Odinjokulen N 1	17	4	5350	23.3	0	3720	0		0	ASTER, 2001–2002	1	0.0037
	Odinjokulen N 2	17	4	4080	15.5	0.36	1690	250				1	0.0017
172 15	Tommelbreen	17	4	9000	31.9	0	5530	0		0	ASTER, 2001–2002	1	0.0055
173 02	Sven Ludvigbreen	17	4	7150	32.2	0.10	2150	120		0	ASTER, 2001–2002	1	0.0021
173 05	Kosterbreen	17	4	11700	44.6	0.57	1260	700				2	0.0088
173 07	Chydeniusbreen	17	4, 19, 43	41000	200.5	1.31	1860	800		+200	ASTER, 2001–2002	2	0.0131
173 08	Polarisbreen	17	19, 29	20000	90.3	0.04	540	100				1	0.0005
173 09	Loderbreen	17	29	6200	11.2	0	640	0				1	0.0006
173 10	Hinlopenbreen 1	17	24, 19	58300	807.2	20.15	7650	3500	-158	-150	ASTER, 2001–2006	3	0.1530
	Hinlopenbreen 2	17	19, 24, 43, GISICE	36400	247.0	0	1650	0				1	0.0016
174 01	Vaigattbreen	17	24,19	9200	67.5	0	6160	0				1	0.0062
174 02	Alfarvegen	17	24	10700	65.6	0	2760	0				1	0.0028
174 04	Moltkebreen	17	6, 7	5000	7.9	0.08	1950	170	-8	-17	ASTER, 2003–2006	1	0.0020
174 06	Hochstatterbreen	17	6, 24, 19, 7	31600	589.2	0.64	12050	150	-38	-50	ASTER, 2003–2006	1	0.0120
174 07	nameless	17	6	9100	36.1	0.26	2170	150	-50	-27	ASTER, 2003–2006	1	0.0022
174 08	Koristkabreen	17	6	14300	50.0	0	1720	0				1	0.0017
174 09	Hannbreen	17	6	9200	22.8	0	980	0		0	ASTER, 2003–2005	1	0.0010

N 4W2 NORAUSTLANDET

Region 21 – NORDAUSTLANDET S

Ident	Glacier name	Region	Image Nb	Lg [m]	Ag [km²]	Ac [km²]	Ice-cliff [m]	Lc [m]	R_1 [m]	R_2 [m]	Front position change (years) and source	Ft	Qc [km³ yr⁻¹]
211 01	Storoyjokulen	21	42			0	12040	0				1	0.0120
211 02	Worsleybreen	21	42			0	4810	0				1	0.0048
211 03	nameless	21	42			0.92	6010	160				1	0.0060
211 04	nameless	21	42			2.77	15890	300				2	0.1112
211 05	nameless	21	42			0	13340	0				1	0.0133
211 06	nameless	21	42			1.25	18880	400				2	0.1322
211 07	nameless	21	42			0	9980	0				1	0.0100
211 08	nameless	21	42, 32			11.22	32860	1050				1	0.0329
211 09	nameless	21	42, 33			0.67	22520	260				1	0.0225
211 10	Brasvellbreen	21	42, 33			6.85	50250	600				1	0.0502
211 13	Mariebreen	21	29			0	1360	0				1	0.0014

Region 22 – NORDAUSTLANDET W

Ident	Glacier name	Region	Image Nb	Lg [m]	Ag [km²]	Ac [km²]	Ice-cliff [m]	Lc [m]	R_1 [m]	R_2 [m]	Front position change (years) and source	Ft	Qc [km³ yr⁻¹]
221 01	Glitnefonna Ne	22	29			0.33	770	500				2	0.0054
221 02	Palanderbreen	22	31, 34			2.84	2040	2500				3	0.0407
221 03	Ericabreen	22	31, 34			0	1310	0				1	0.0013
221 04	nameless	22	31, 34			0	680	0				1	0.0007
222 02	nameless	22	34, 35			2.57	3720	900				2	0.0260
222 03	Etonbreen	22	34, 35			3.65	5880	700				2	0.0411
222 06	Bodleybreen	22	34, 35			41.36	3080	1200				3	0.0615
222 08	Aldousbreen	22	34, 35			5.28	4720	1400				3	0.0944
222 09	Frazerbreen	22	34, 35			5.01	5220	1300				3	0.1043
222 10	Idunbreen	22	4			5.57	4170	2000				3	0.0834
222 11	Bragebreen	22	4			2.05	6650	800				2	0.0466
222 12	Gimlebreen	22	4, 28			0.55	6820	300				2	0.0477

Region 23 – NORDAUSTLANDET NW

Ident	Glacier name	Region	Image Nb	Lg [m]	Ag [km²]	Ac [km²]	Ice-cliff [m]	Lc [m]	R_1 [m]	R_2 [m]	Front position change (years) and source	Ft	Qc [km³ yr⁻¹]
232 03	S Franklinbreen	23	27			14.29	5330	5300				3	0.1065
232 04	N Franklinbreen	23	27			1.01	1590	800				2	0.0111

Region 24 – NORDAUSTLANDET N

Ident	Glacier name	Region	Image Nb	Lg [m]	Ag [km²]	**Ac** [km²]	Ice-cliff [m]	Lc [m]	R_1 [m]	R_2 [m]	Front position change (years) and source	Ft	Qc [km³ yr⁻¹]
241 03	Sabinebreen	24	42			0	3540	0				1	0.0035
242 01	Rijpbreen	24	31, 42			8.16	2960	5600				2	0.0207

Region 25 – NORDAUSTLANDET NE

Ident	Glacier name	Region	Image Nb	Lg [m]	Ag [km²]	Ac [km²]	Ice-cliff [m]	Lc [m]	R_1 [m]	R_2 [m]	Front position change (years) and source	Ft	Qc [km³ yr⁻¹]
251 05	nameless	25	36			1.44	1400	1000				3	0.0280
251 06	Duvebreen	25	36			1.13	1900	1000				3	0.0380
252 01	Schweigaardenbreen	25	36, 42			3.33	5250	2000				3	0.1049
252 02	Nilsenbreen	25	36			0.20	3470	500				2	0.0243
252 04	Leighbreen	25	42			5.72	25880	600				2	0.1812

N 4W3 SVALBARD SE

Region 31 – EGDEØYA

Ident	Glacier name	Region	Image Nb	Lg [m]	Ag [km²]	Ac [km²]	Ice-cliff [m]	Lc [m]	R_1 [m]	R_2 [m]	Front position change (years) and source	Ft	Qc [km³ yr⁻¹]
311 06	Deltabreen	31	2	14300	133.9	0	5780	0		-38	ASTER, 2001–2004	1	0.0058
313 18	Stonebren	31	30	37200	632.1	7.17	56210	500				2	0.3935
313 19	Kong Johans Bre	31	30	14000	81.6	1.30	6720	300				2	0.0471

Region 32 – BARENTSØYA

Ident	Glacier name	Region	Image Nb	Lg [m]	Ag [km²]	Ac [km²]	Ice-cliff [m]	Lc [m]	R_1 [m]	R_2 [m]	Front position change (years) and source	Ft	Qc [km³ yr⁻¹]
321 01	Freemanbreen	32	8	16600	72.2	0.12	2060	150				1	0.0021
321 02	Duckwitzbreen	32	25	18000	72.6	0	230	0				1	0.0002
322 02	Besselsbreen	32	25	20000	128.6	0.66	6460	300				1	0.0065

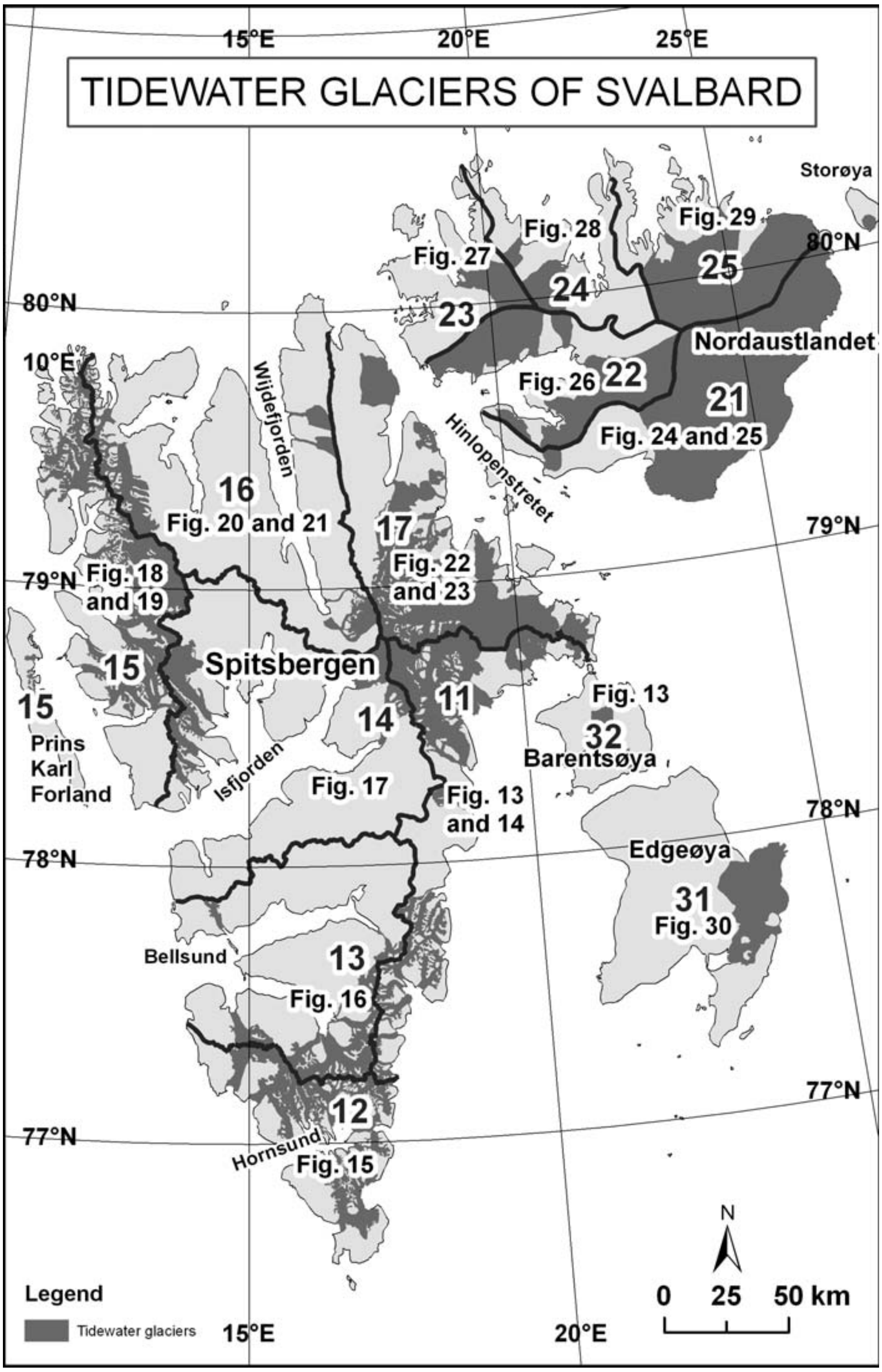

Fig. 12. Location map showing regions of Svalbard distinguished by Hagen *et al*. (1993) and numbers of sheets of maps where tidewater glaciers are present (Figs 13–30).

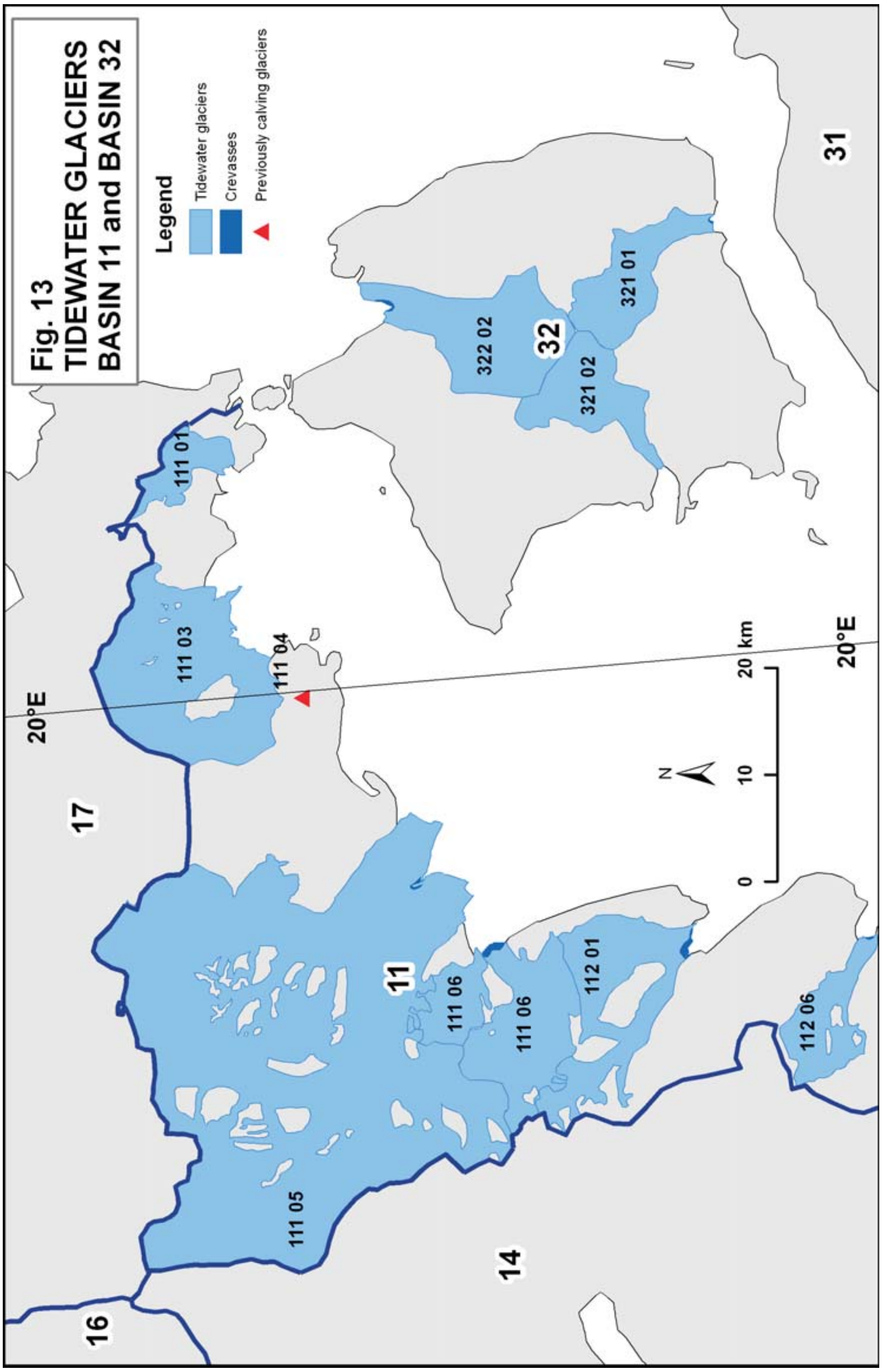

Fig. 13
TIDEWATER GLACIERS
BASIN 11 and BASIN 32

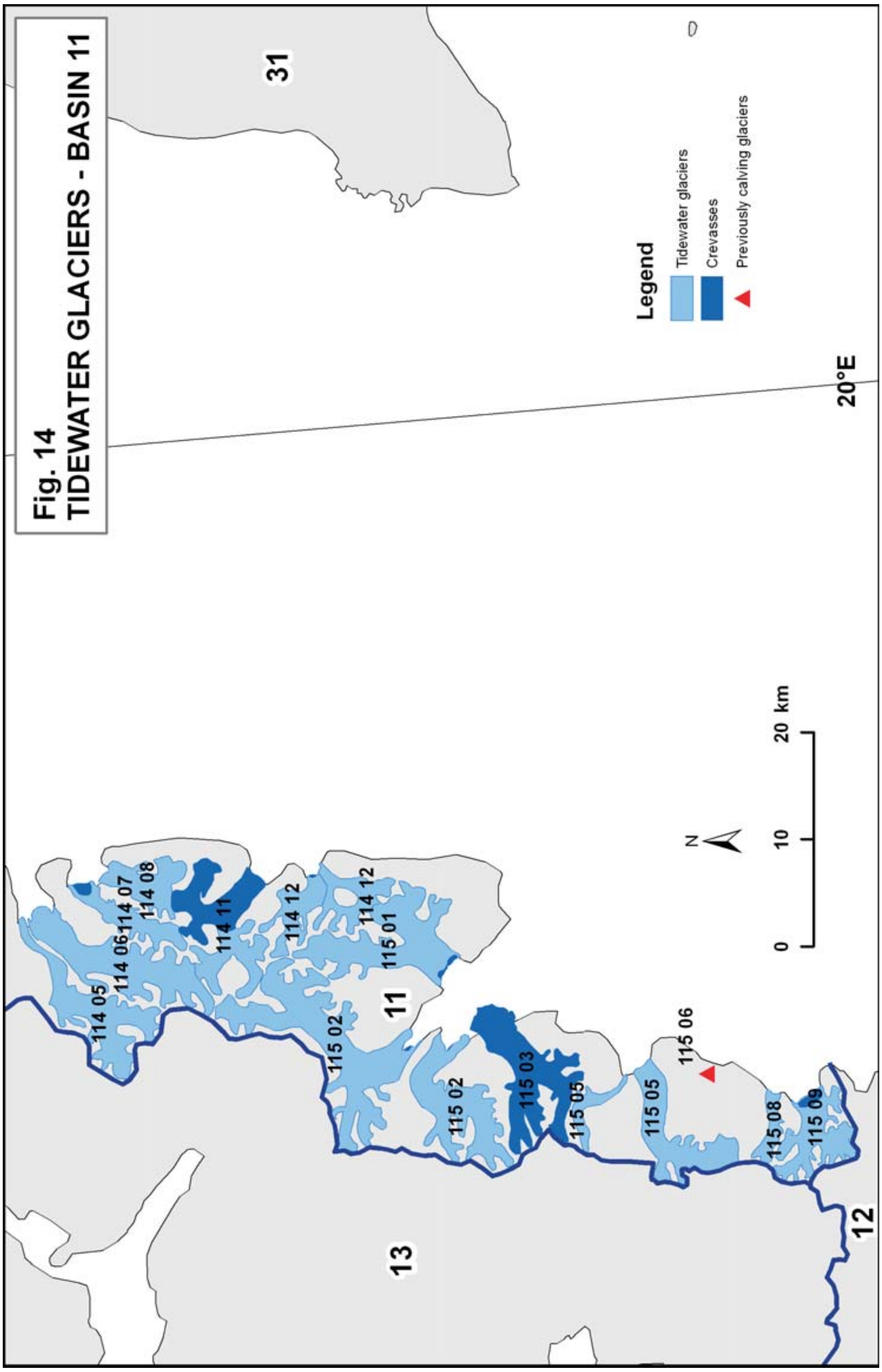
Fig. 14
TIDEWATER GLACIERS - BASIN 11
Legend
Tidewater glaciers
Crevasses
Previously calving glaciers
20°E
0
10
20 km
N
31
11
12
13
114 05
114 06
114 07
114 08
114 11
114 12
114 12
115 01
115 02
115 02
115 03
115 05
115 05
115 06
115 08
115 09

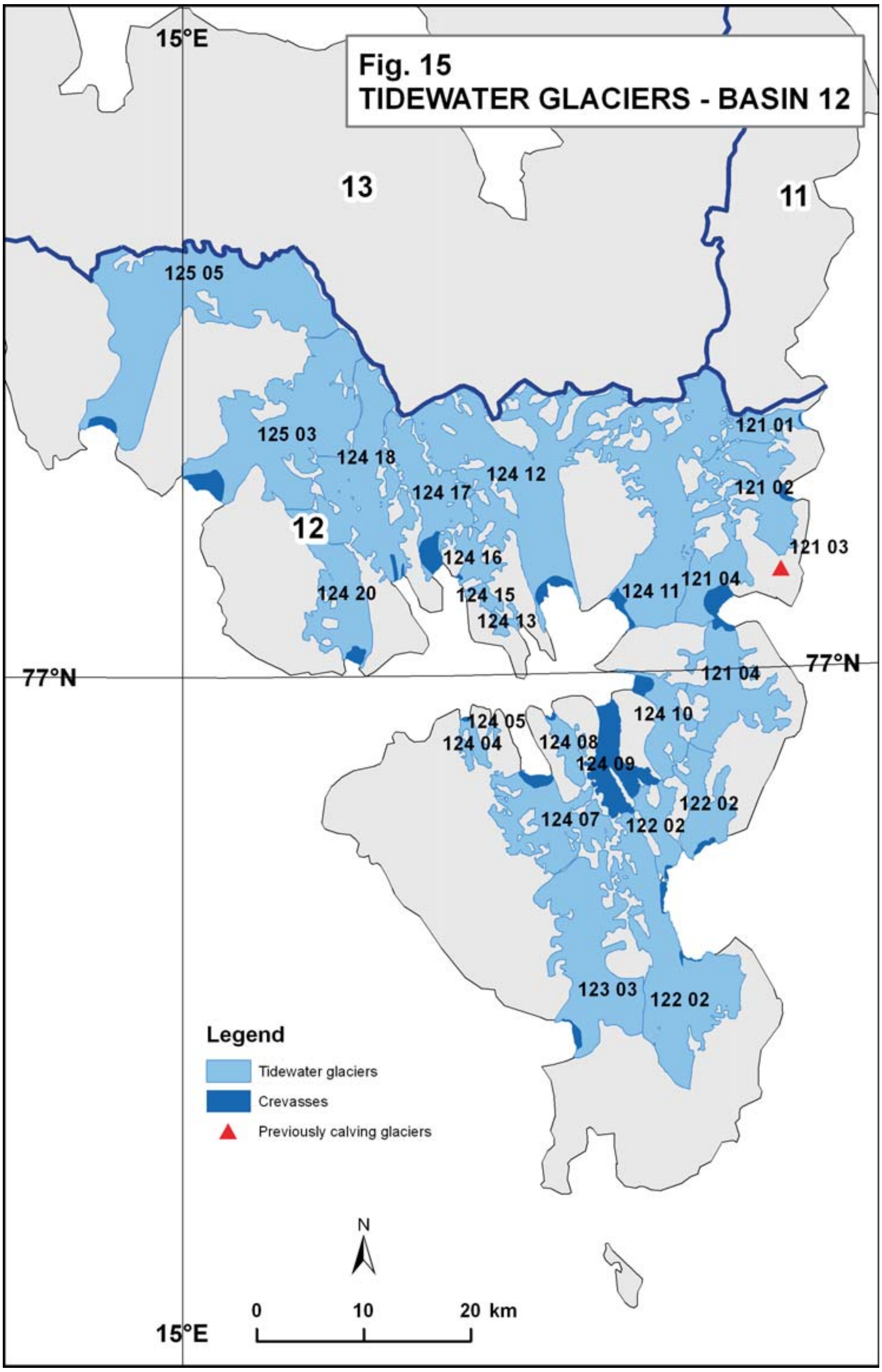
Fig. 15
TIDEWATER GLACIERS - BASIN 12
15°E
13
11
125 05
125 03
124 18
124 17
124 12
121 01
121 02
121 03
12
124 16
124 20
124 15
124 13
124 11
121 04
77°N
121 04
124 05
124 04
124 08
124 09
124 10
122 02
124 07
122 02
123 03
122 02
Legend
Tidewater glaciers
Crevasses
Previously calving glaciers
N
0
10
20 km
15°E

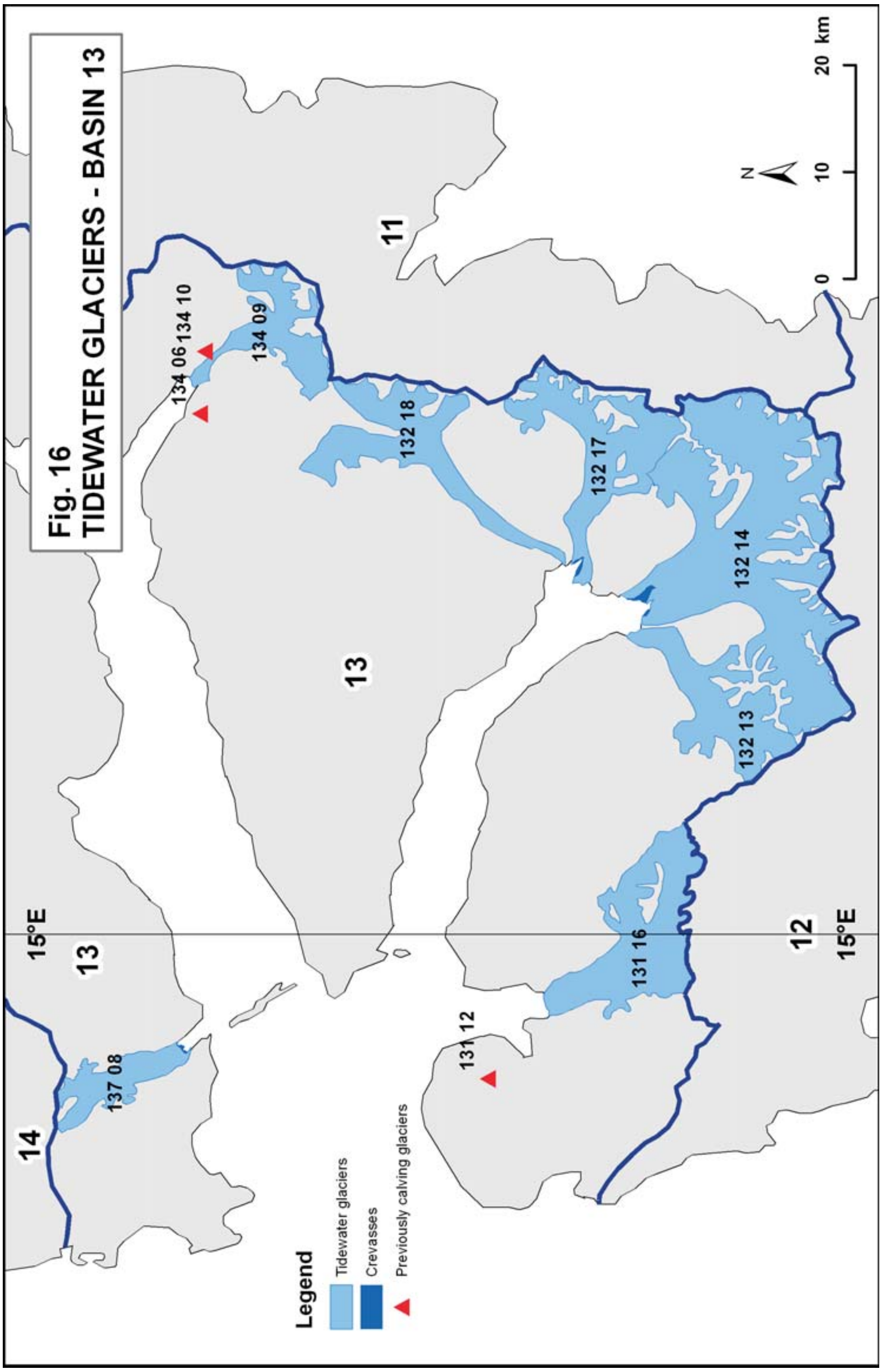
Fig. 16
TIDEWATER GLACIERS - BASIN 13
134 06
134 10
134 09
132 18
132 17
132 14
132 13
131 16
131 12
137 08
11
13
12
14
15°E
N
0 10 20 km
Legend
Tidewater glaciers
Crevasses
Previously calving glaciers

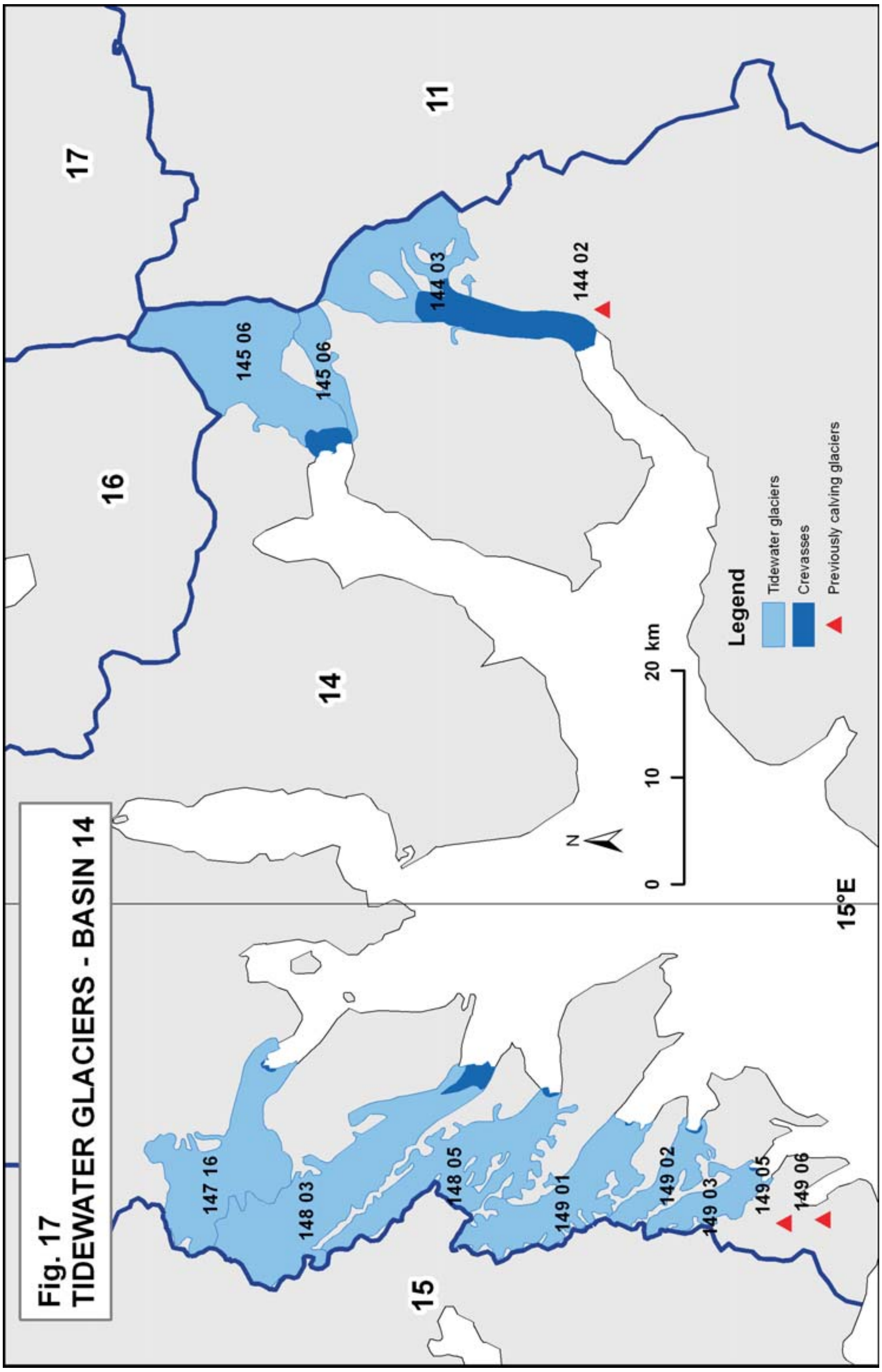

Fig. 17
TIDEWATER GLACIERS - BASIN 14

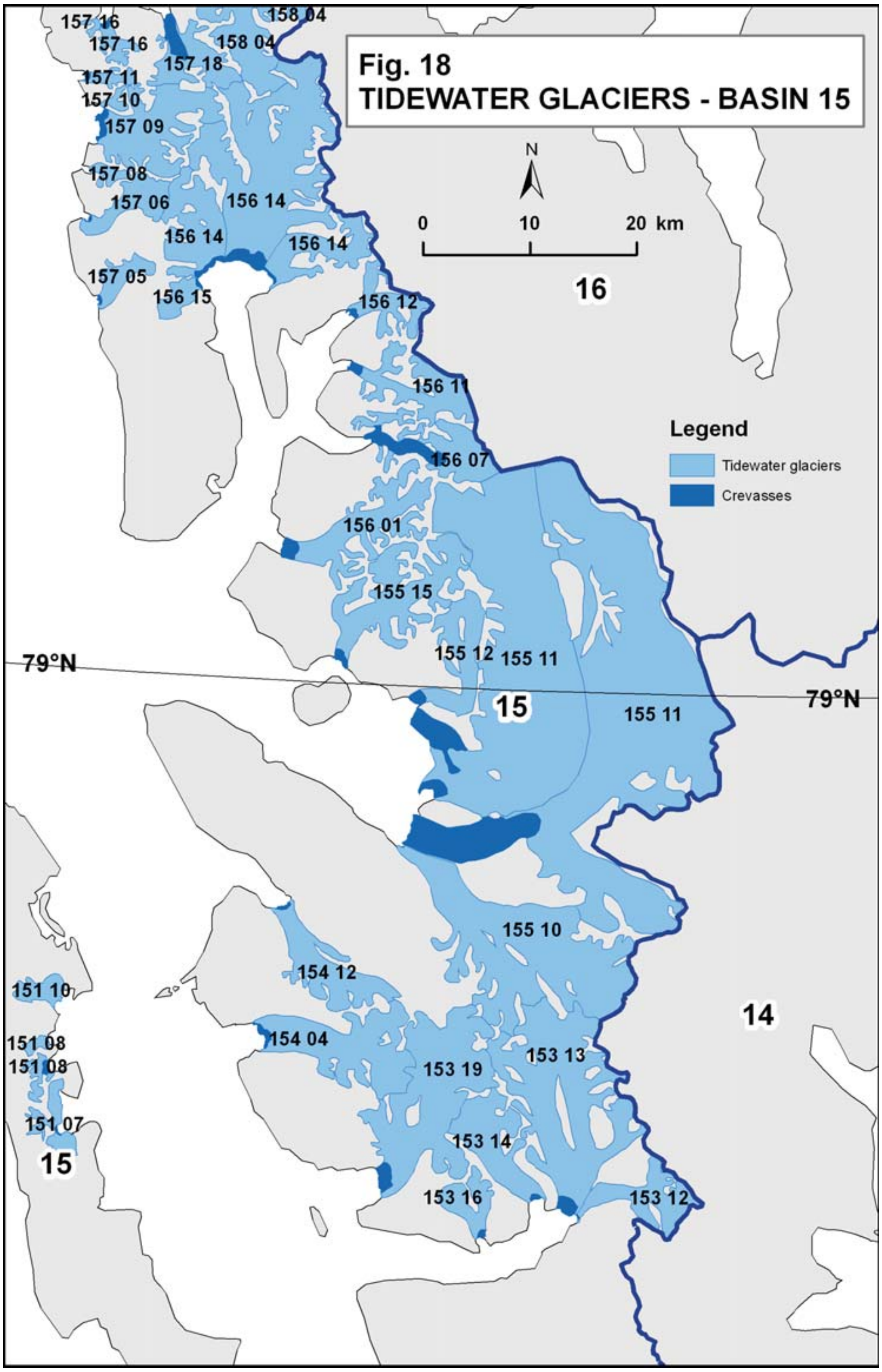
Fig. 18
TIDEWATER GLACIERS - BASIN 15
Legend
Tidewater glaciers
Crevasses
0 10 20 km
N
16
15
14
79°N
157 16
157 18
158 04
157 11
157 10
157 09
157 08
157 06
156 14
157 05
156 15
156 12
156 11
156 07
156 01
155 15
155 12
155 11
155 10
154 12
154 04
153 19
153 13
153 14
153 16
153 12
151 10
151 08
151 07

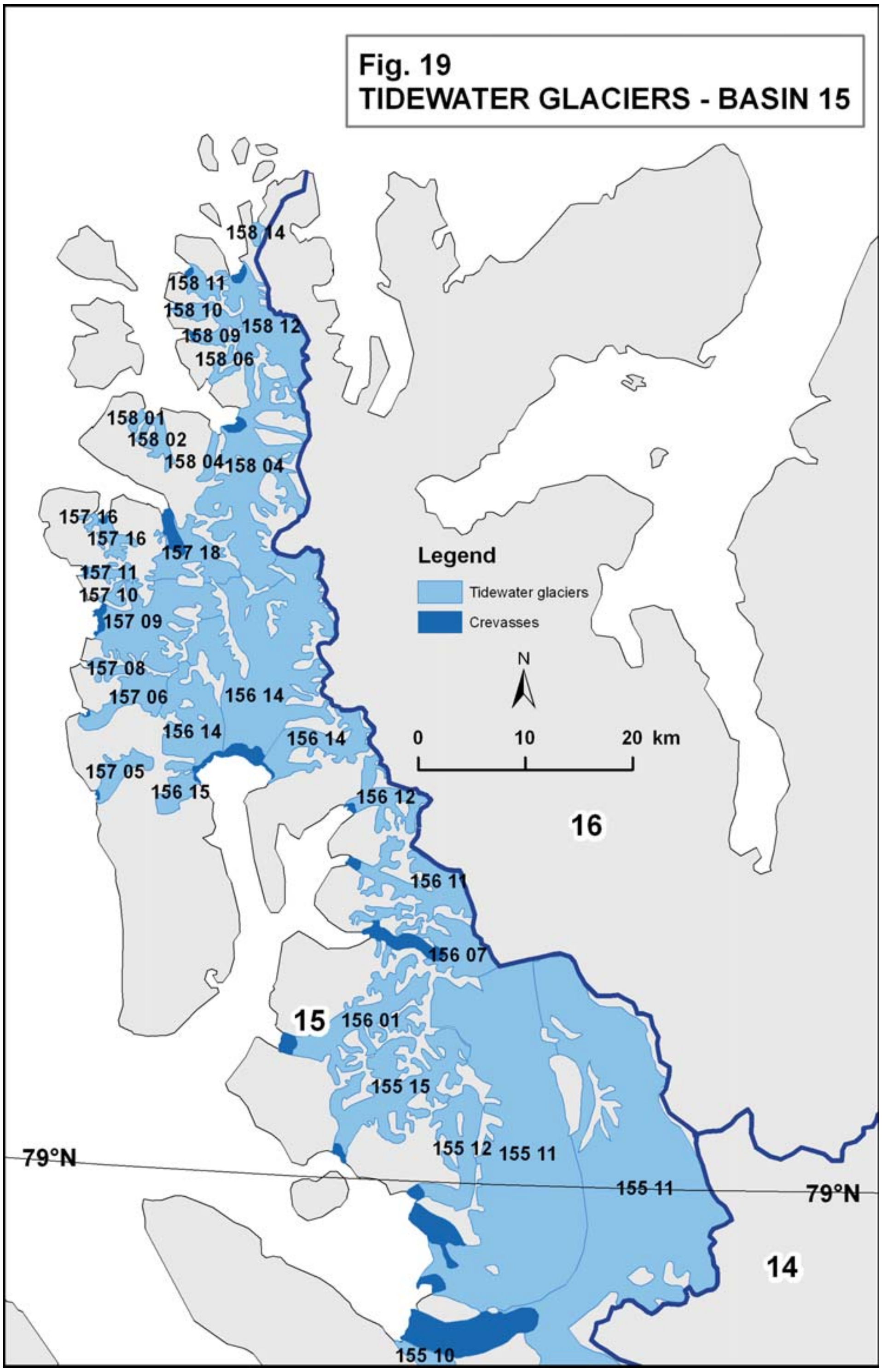
Fig. 19
TIDEWATER GLACIERS - BASIN 15
158 14
158 11
158 10
158 09
158 12
158 06
158 01
158 02
158 04
158 04
157 16
157 16
157 18
157 11
157 10
157 09
157 08
157 06
156 14
156 14
156 14
157 05
156 15
156 12
156 11
156 07
15
156 01
155 15
155 12
155 11
155 11
155 10
79°N
79°N
16
14
Legend
Tidewater glaciers
Crevasses
N
0
10
20 km

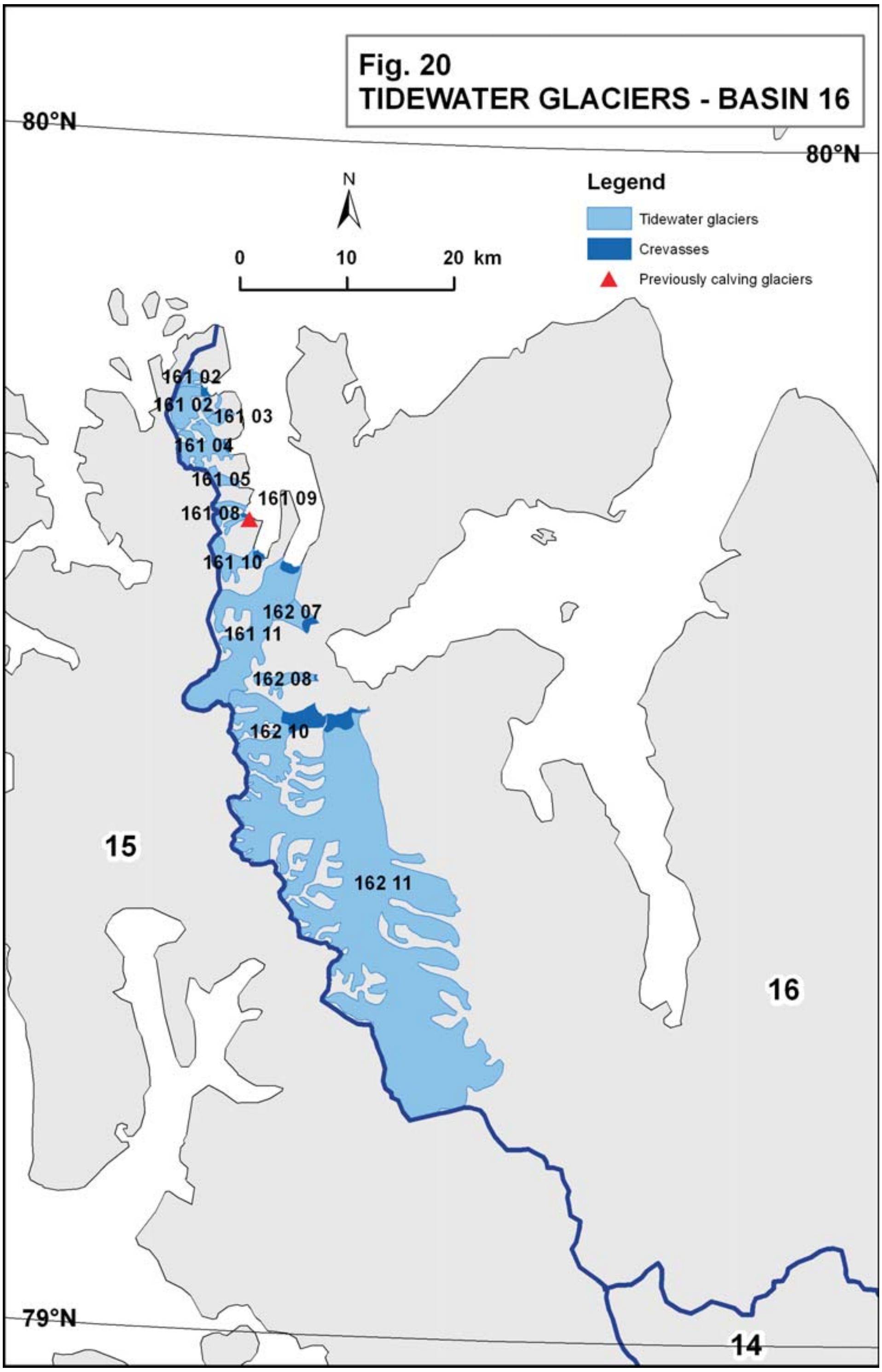
Fig. 20
TIDEWATER GLACIERS - BASIN 16
80°N
80°N
N
0
10
20 km
Legend
Tidewater glaciers
Crevasses
Previously calving glaciers
161 02
161 02
161 03
161 04
161 05
161 09
161 08
161 10
162 07
161 11
162 08
162 10
162 11
15
16
79°N
14

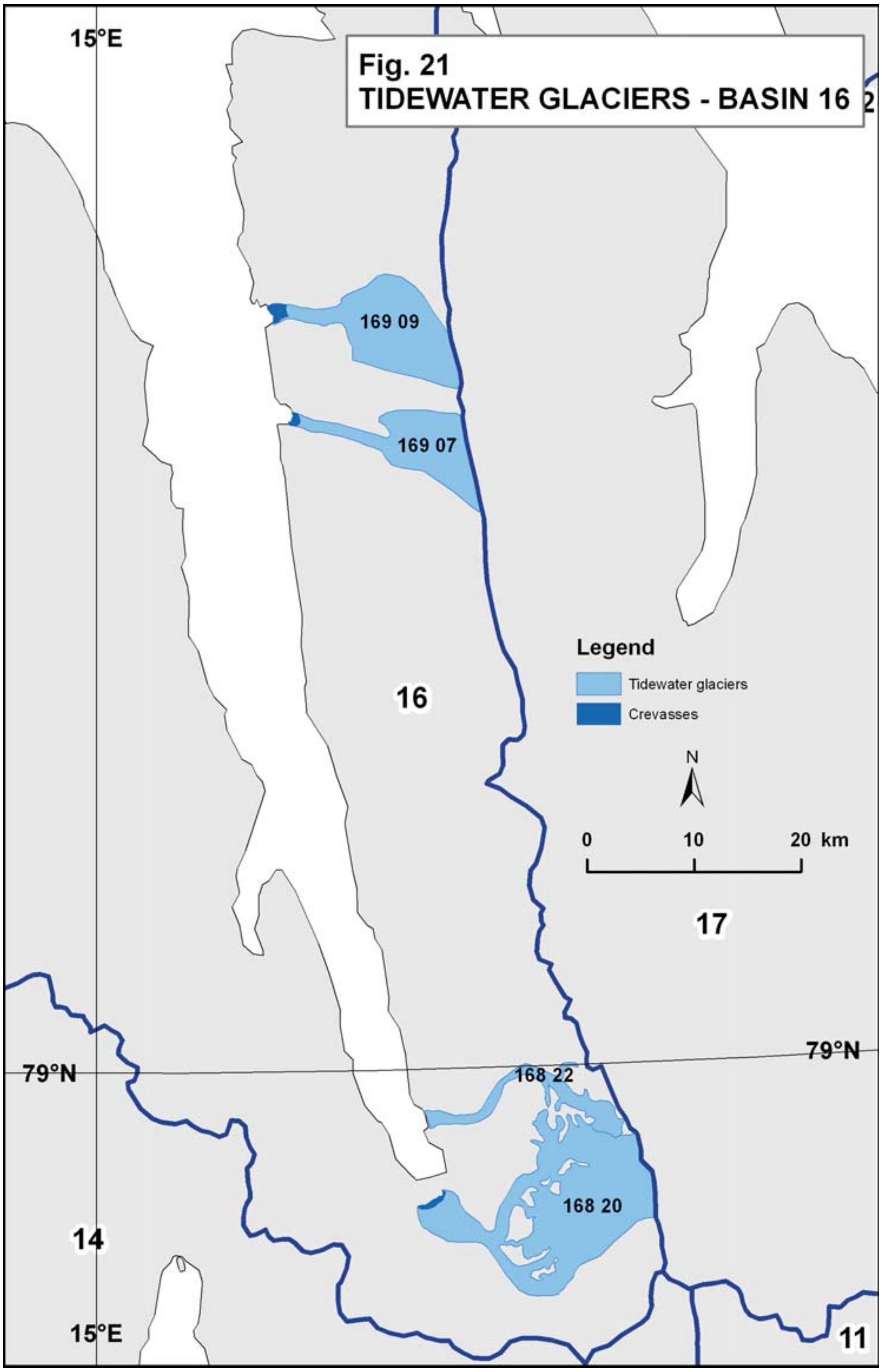
Fig. 21
TIDEWATER GLACIERS - BASIN 16
15°E
169 09
169 07
16
Legend
Tidewater glaciers
Crevasses
N
0
10
20 km
17
79°N
79°N
168 22
168 20
14
15°E
11

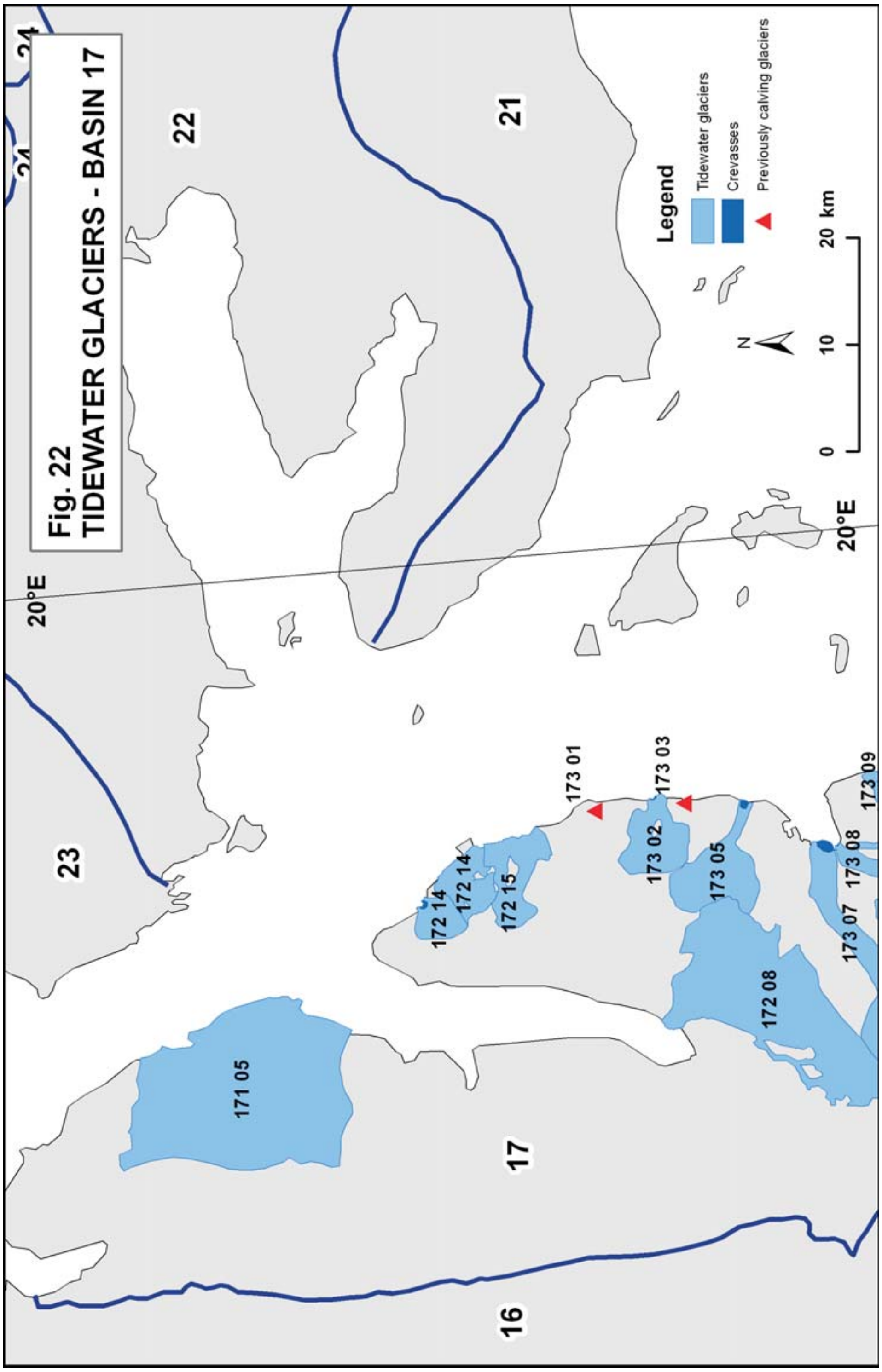
Fig. 22
TIDEWATER GLACIERS - BASIN 17
Legend
Tidewater glaciers
Crevasses
Previously calving glaciers
N
0
10
20 km
20°E
20°E
24
24
22
21
23
17
16
171 05
172 14
172 14
172 15
172 08
173 01
173 03
173 02
173 05
173 07
173 08
173 09

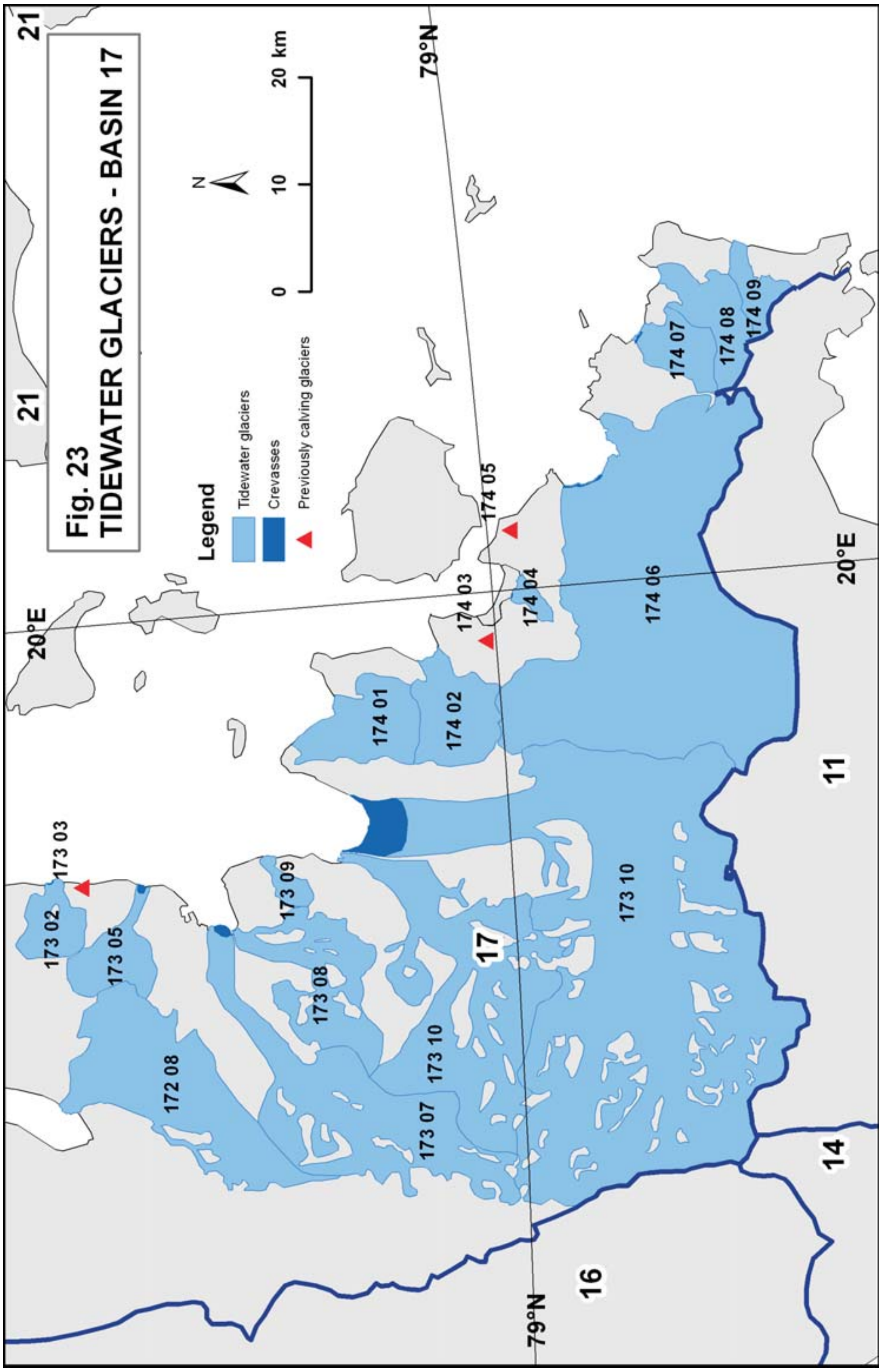

Fig. 23
TIDEWATER GLACIERS - BASIN 17

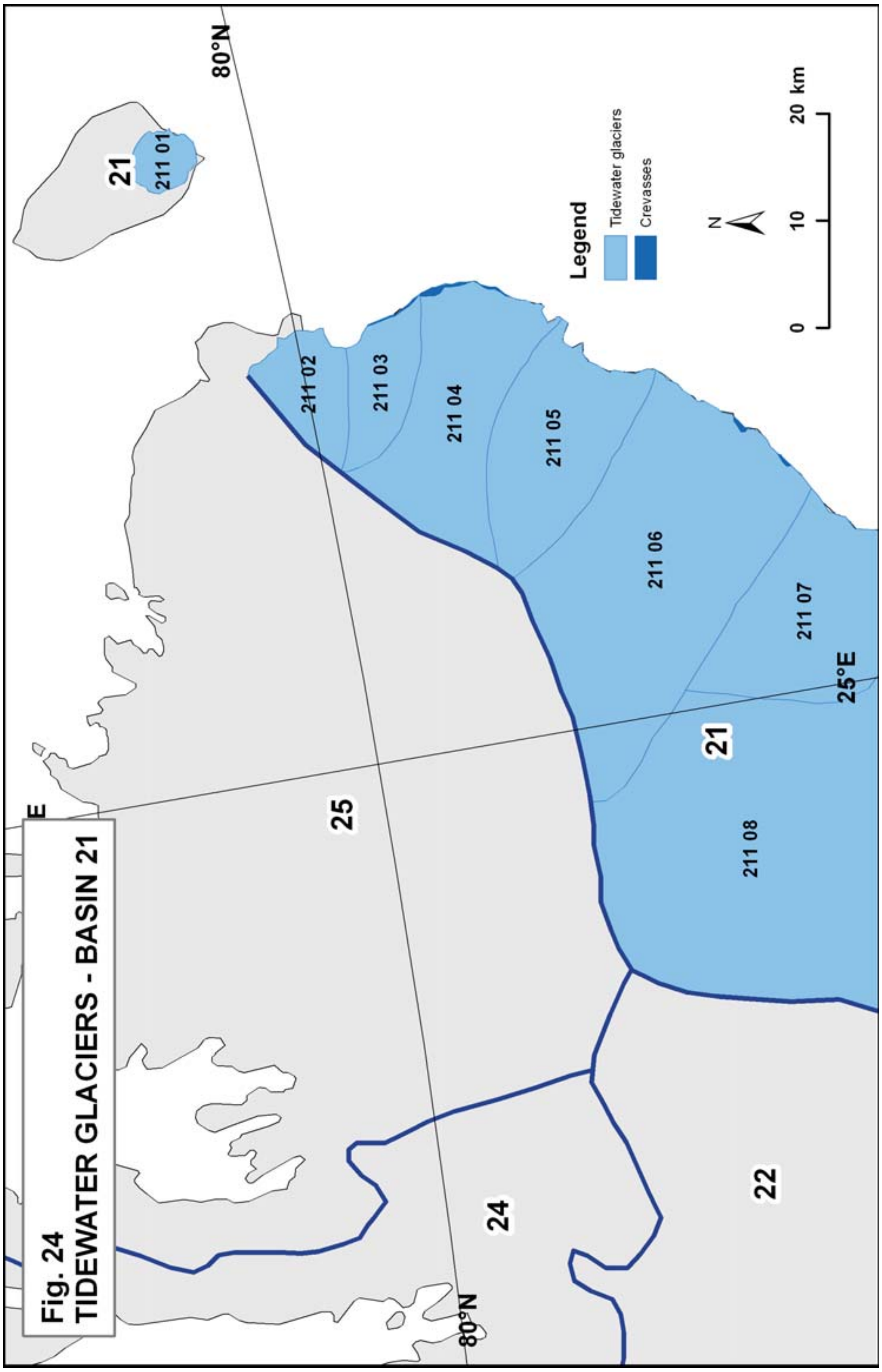

Fig. 24
TIDEWATER GLACIERS - BASIN 21

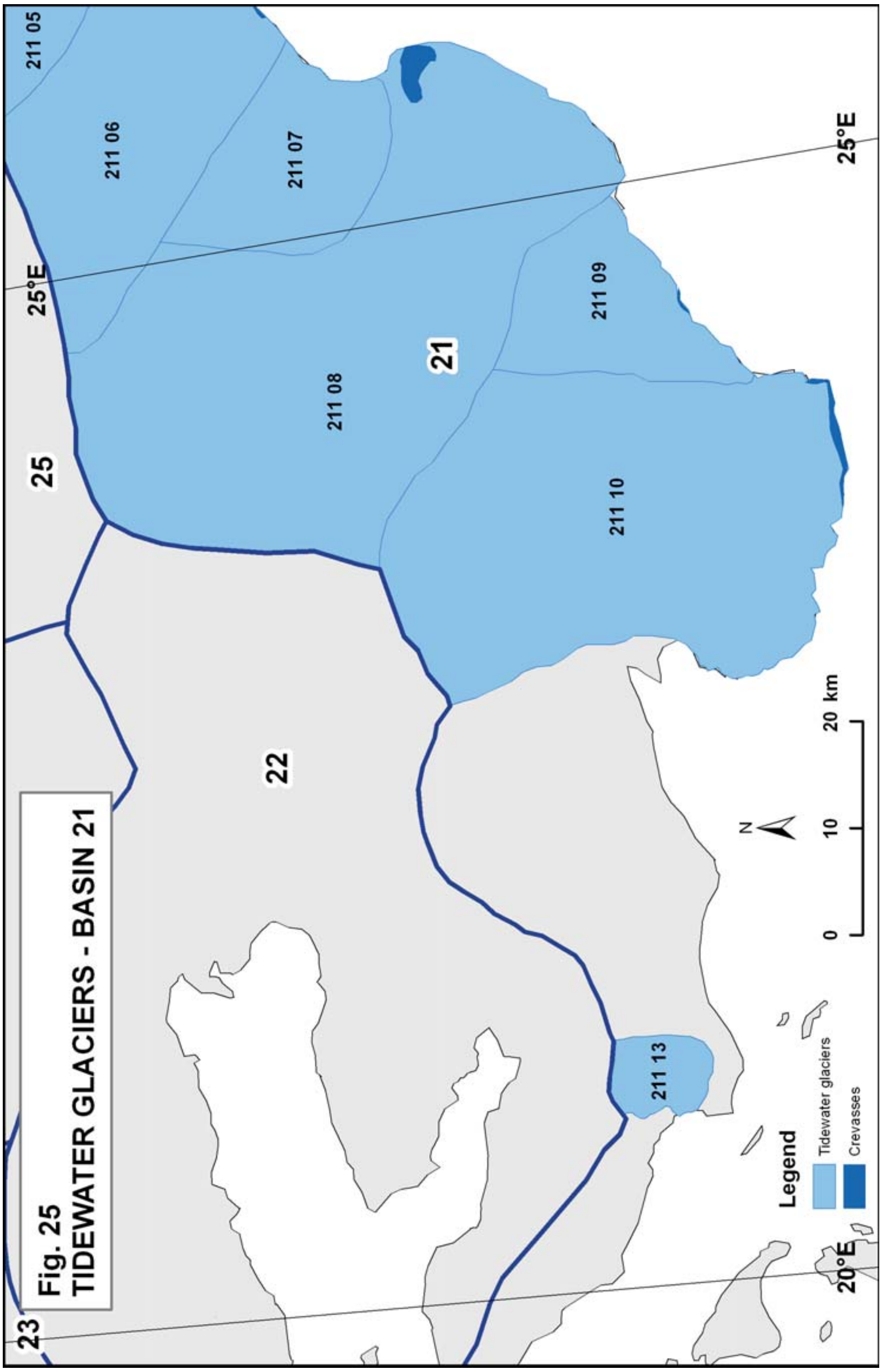

Fig. 25
TIDEWATER GLACIERS - BASIN 21

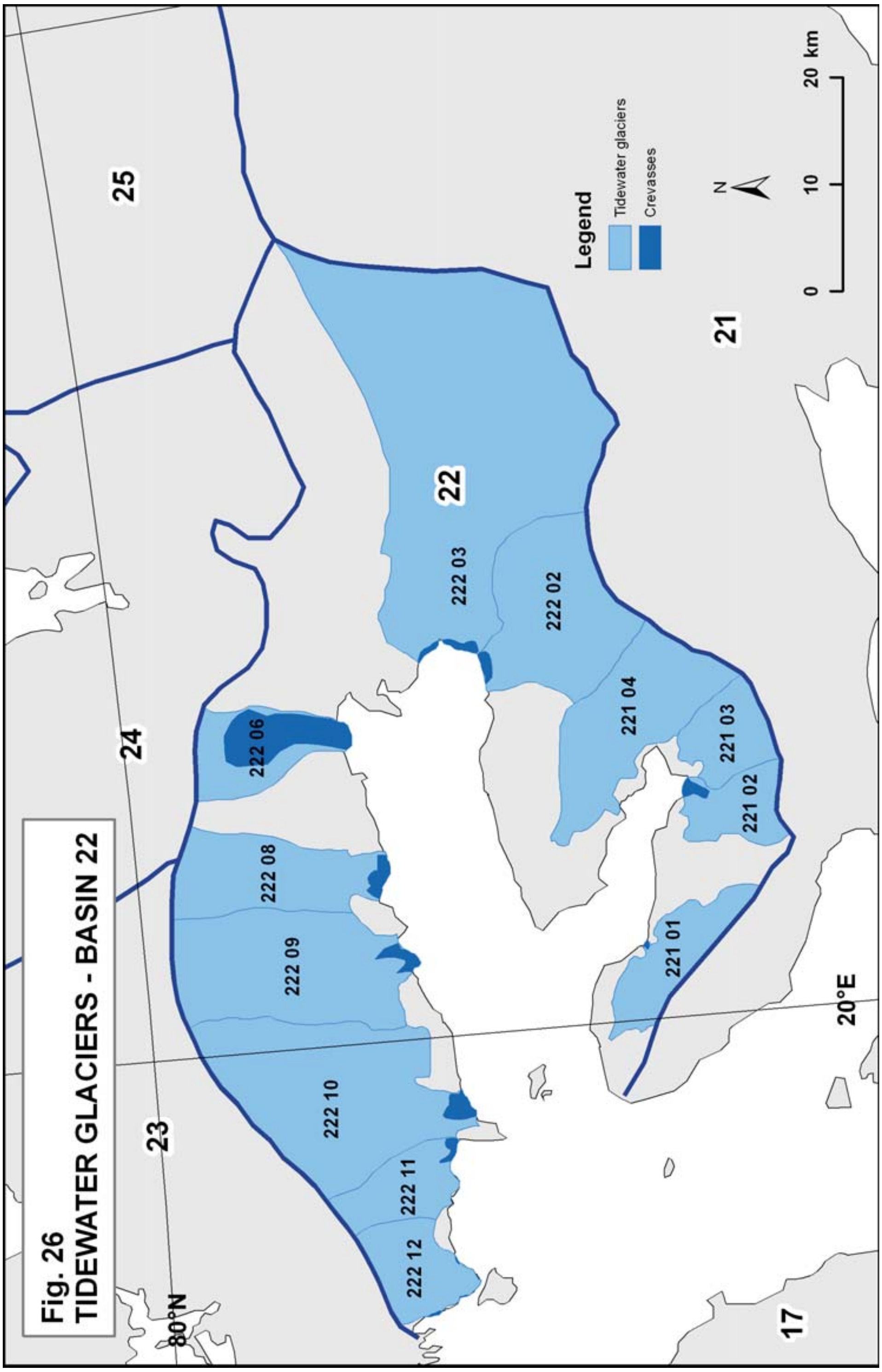

Fig. 26
TIDEWATER GLACIERS - BASIN 22

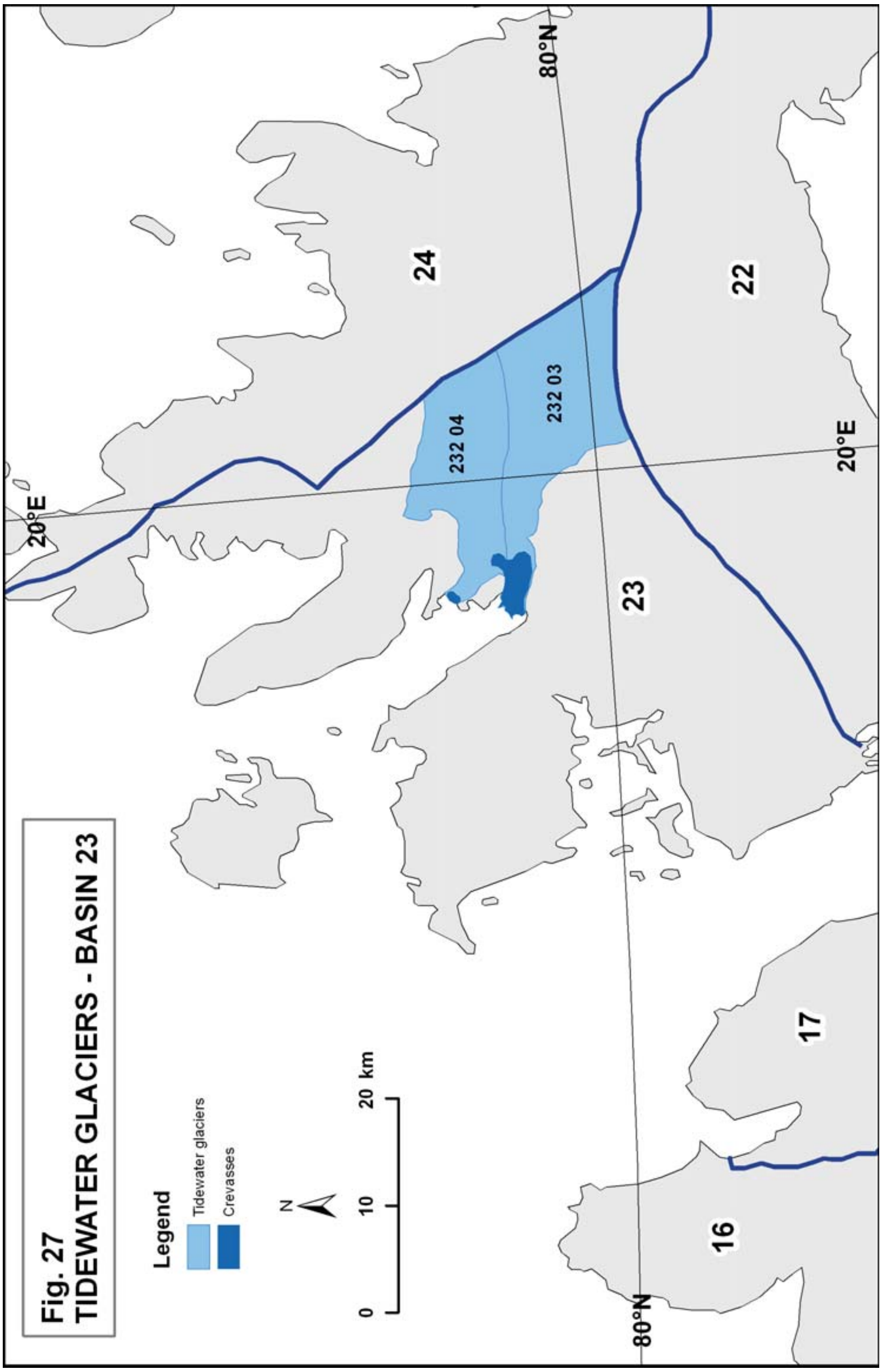

Fig. 27
TIDEWATER GLACIERS - BASIN 23

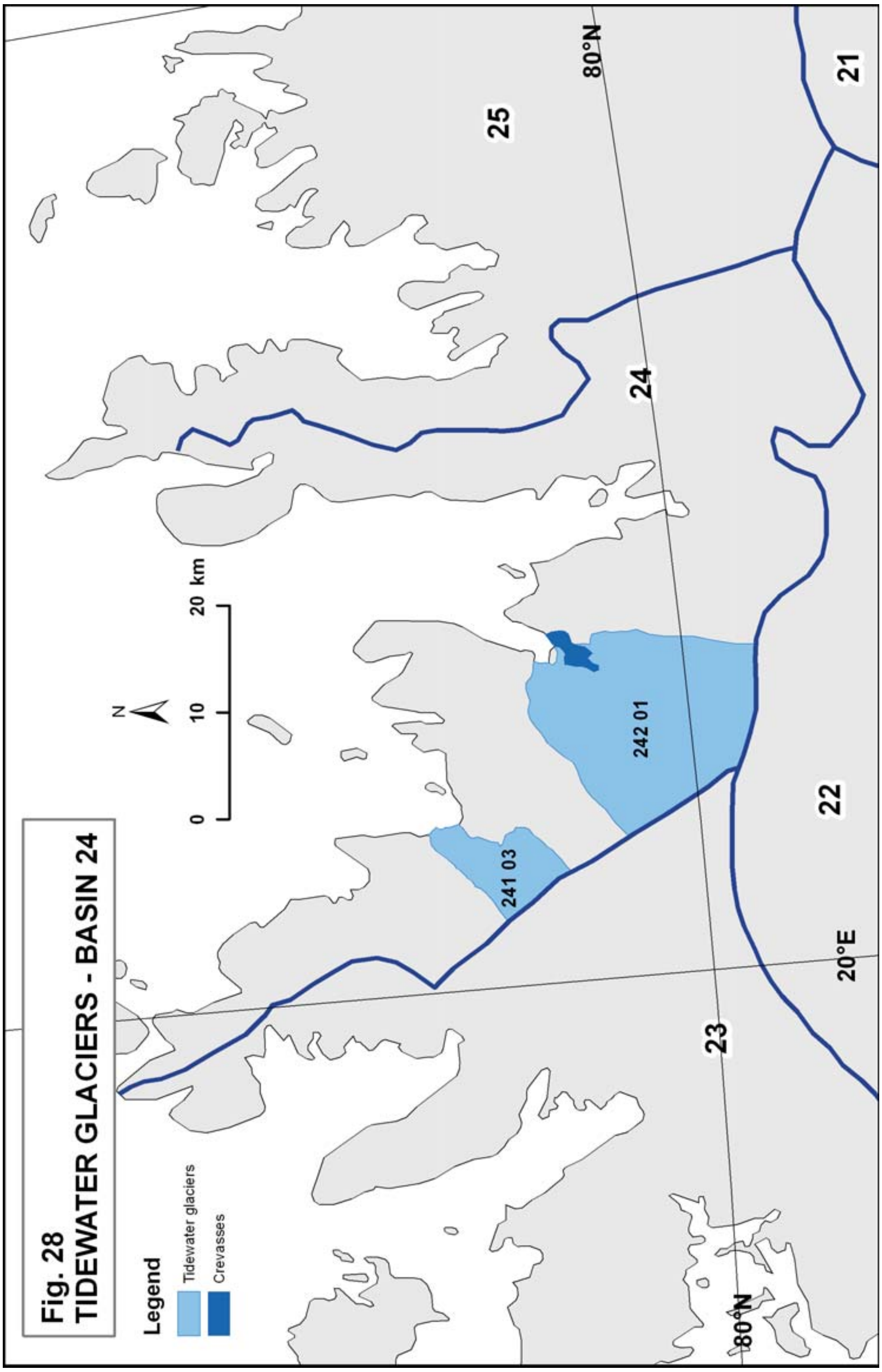
Fig. 28
TIDEWATER GLACIERS - BASIN 24
Legend
Tidewater glaciers
Crevasses
N
0
10
20 km
241 03
242 01
21
22
23
24
25
80°N
80°N
20°E

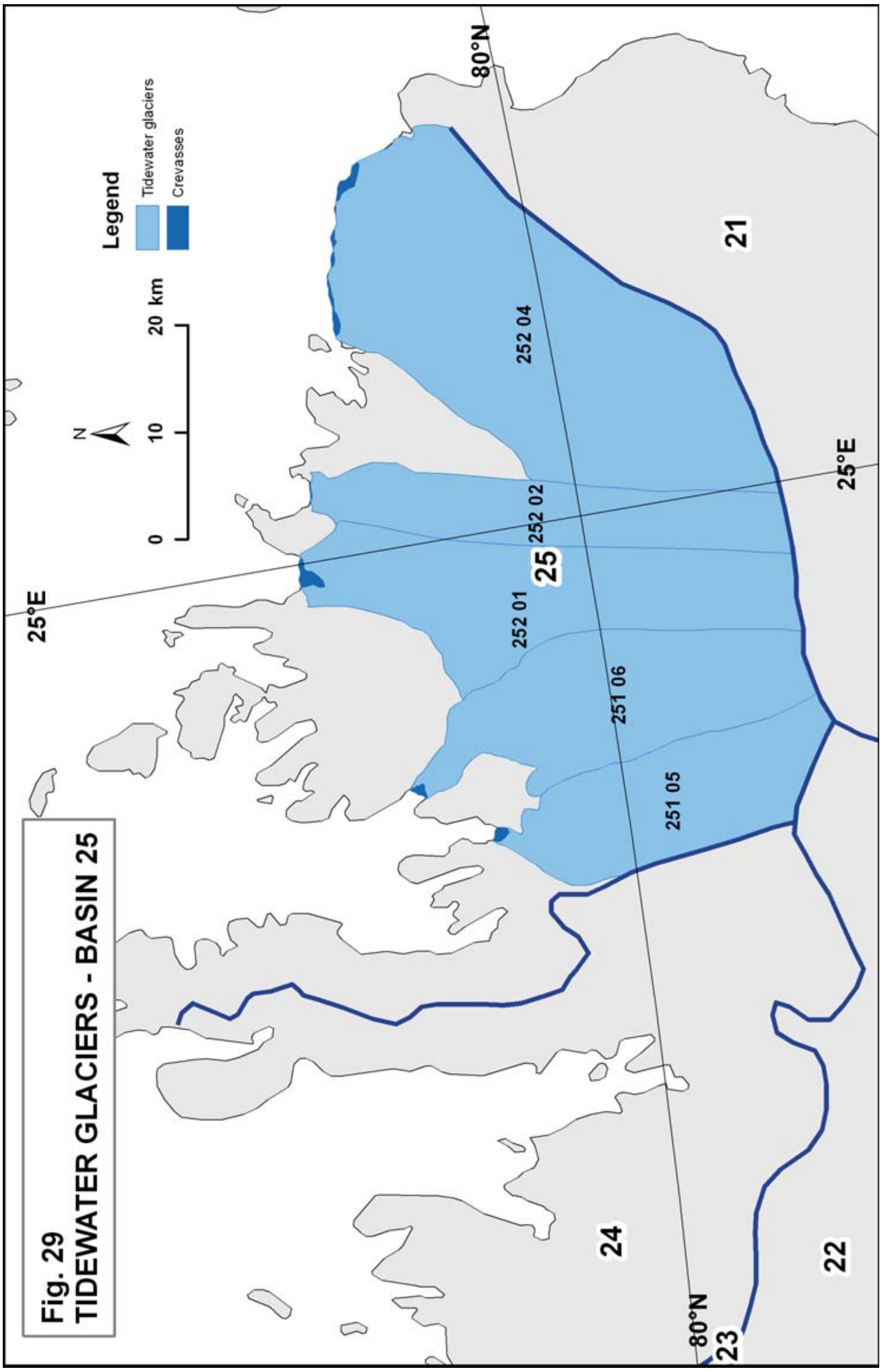

Fig. 29
TIDEWATER GLACIERS - BASIN 25

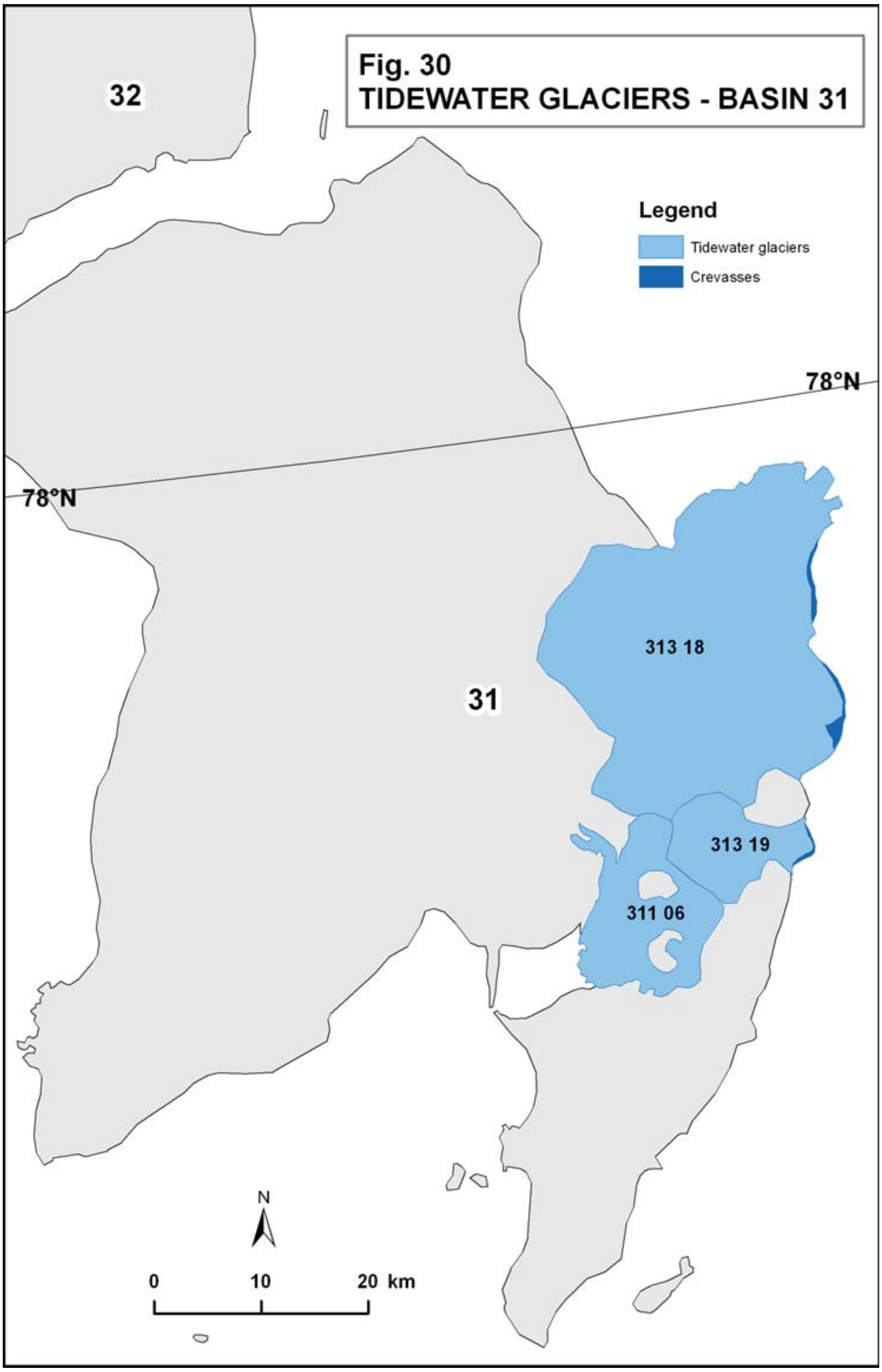
Fig. 30
TIDEWATER GLACIERS - BASIN 31
Legend
Tidewater glaciers
Crevasses
32
31
78°N
78°N
313 18
313 19
311 06
N
0
10
20 km