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ORIGINAL ARTICLE

The Kongsfjorden Channel System offshore NW Svalbard: downslope sedimentary processes in a contour-current-dominated setting

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Abstract Submarine channel systems on and off glaciated continental margins can be up to hundreds of kilometres long, tens of kilometres wide and hundreds of metres deep. They result from repeated erosion and various downslope processes predominantly during glacial periods and can, therefore, provide valuable tools for the reconstruction of past ice-sheet dynamics. The Kongsfjorden Channel System (KCS) on the continental slope off northwest Svalbard provides evidence that downslope sedimentary processes are locally more dominant than regional along-slope sedimentation. It is a relatively short channel system (~120 km) that occurs at a large range of water depths (~250–4000 m) with slope gradients varying between 0° and 20°. Multiple gullies on the Kongsfjorden Trough Mouth Fan merge to small channels that further merge to a main channel. The overall location of the channel system is controlled by variations in slope gradients and the ambient regional bathymetry. The widest and deepest incisions occur in areas of the steepest slope gradients. The KCS has probably been active since ~1 Ma when glacial activity on Svalbard increased and grounded ice expanded to the shelf break off Kongsfjorden repeatedly. Activity within the system was probably highest during glacials. However, reduced activity presumably took place also during interglacials.

Keywords Kongsfjorden Channel System · Svalbard · Continental slope · Contourite drifts · Glaciated continental margin

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Introduction

The slopes of glaciated continental margins allow the study of a variety of sedimentary processes related to along-slope and downslope sedimentation (e.g. [66, 71]). Contourite drifts along the margins and within the adjacent deep sea suggest that bottom currents flowing parallel to the slopes can dominate the long-term sedimentation at local to regional scales (e.g. [7, 21, 23, 33, 36, 56, 57]). However, gullies, channels and canyons provide evidence of repeated and focused downslope processes leading to erosion and slope incision over time. Gullies are relatively small, confined channels, typically in the order of tens of metres deep (e.g. [19], and references therein). They are suggested to be the first erosional features forming on steeply dipping slopes in both terrestrial and marine settings [5, 34]. The formation mechanisms of submarine gullies remain poorly constrained. It has been suggested that they can form from a variety of mechanisms including small-scale mass wasting or erosion by cascading dense water masses during glaciations (e.g. [6, 19, 34, 72]). Submarine channel–levee systems can have vertical reliefs of up to several hundreds of metres and lengths of several hundreds of kilometres (e.g. [64, 65]). Channels form probably also due to downslope flow of dense water rejected from brine formation, as well as turbidity flows beyond the mouths of

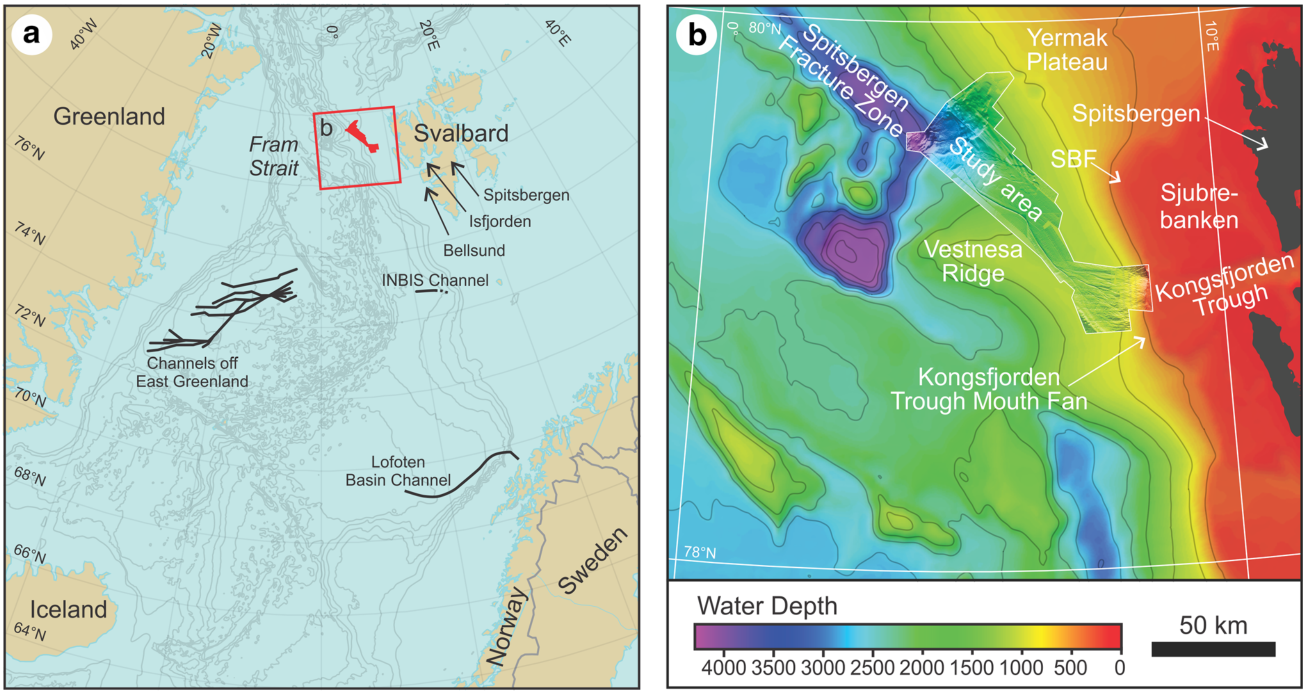

Fig. 1 Location of the study area. **a** Overview map of the Nordic Seas and approximate locations of channel systems off East Greenland, the Lofoten Basin Channel, the INBIS Channel, as well as the study area (for details and references, see Table 1). **b** Regional setting of the study area. *SBF* Sjubrebanken Fan

glacial troughs, when grounded ice extends to the shelf break during full glacials (e.g. [8, 43, 48, 71]). The largest canyons are up to 2.6 km deep and 100 km wide [46]. Multiple factors contribute to the formation of canyons, in particular mass wasting [63], but also tectonic activity (e.g. [42]). Canyon formation can originate at both the lower and upper slopes (see [59], and references therein).

Multiple studies have been performed on channel systems on glaciated continental margins extending from the shelf break to abyssal plains (e.g. [29, 37, 43, 44, 48, 58, 71, 73]). In this study, we present swath bathymetry and subbottom profiler data from a channel system on the continental slope off NW Svalbard. The study area is located in a setting dominated by contourite-drift deposition on a narrow continental slope with a large variety of slope gradients, terminating in a mid-ocean spreading zone. We discuss parameters influencing the location and shape, as well as processes maintaining the system. Furthermore, we compare our results with studies of other channel systems to discuss factors controlling the location, origin and maintenance of high-latitude channel systems.

Physiography

The study area is located in the eastern Fram Strait, on the continental slope off NW Spitsbergen the largest island of the Svalbard archipelago (~78°50–79°50′ N; ~4°–9° E) (Fig. 1). Its N–S and E–W extents are 120 and 90 km, respectively. Water depths vary between ~220 m on the outermost continental shelf and ~4200 m in the Spitsbergen Fracture Zone (SFZ). Furthermore, its southernmost reaches cover parts of the northern slope of the Vestnesa Ridge.

The Fram Strait is the only deep-water connection between the Arctic Ocean and the world's oceans. Its opening started during late Oligocene to early Miocene [12, 67]. Ventilated circulation between the Arctic and Atlantic Oceans commenced around 18.2 Ma (millions of years before the present) and exceeded 2000 m water depth since 13.7 Ma [25]. The present-day large-scale hydrography in the Fram Strait is characterised by the northward flowing West Spitsbergen Current (WSC) and the southward flowing East Greenland Current (EGC) on the eastern and western sides of the strait, respectively. However, a general weak southward flow of deep-water masses, as well as the occurrence of gigantic meanders or eddies and the formation of the Return Atlantic Current, causes a more complex hydrography in the central parts of the Fram Strait (RAC; e.g. [13, 20, 62]). A continuous northward flow of water occurs in the study area east of 5° E [4]. Bottom-current velocities exceed 10 cm/s shallower than 800 m. They decrease from 10 to 0 cm/s deeper than 800 m. West of 5° E, bottom currents move southward with velocities of less than 5 cm/s [4].

Contourite-drift deposition dominated the overall sedimentary environment in the eastern Fram Strait since at least 11 Ma and numerous sediment drifts have been identified on the continental slope off western Svalbard, mainly at water depths exceeding 1200 m [7, 21, 23, 24, 41, 57, 61]. However, multiple escarpments north of the study area provide evidence of repeated downslope sediment transport ([10, 50]).

Lithological investigations reveal that the sedimentary environment during the past c. 30,000 years has been dominated by deposition from suspension settling, current modification and ice rafting (e.g. [22, 26]). However, generally coarser sediments, interpreted as mass-transport deposits, accumulated regionally between c. 24,000 and 23,300 cal. years BP, when grounded ice expanded to the shelf break [26].

The shallowest parts of the study area include the northern parts of the Kongsfjorden Trough Mouth Fan (TMF), a protrusion of the continental shelf off NW Spitsbergen (Fig. 1). This fan formed during multiple glaciations when fast-flowing ice streams, draining ice sheets covering the Svalbard archipelago, reached the shelf break repeatedly, delivering substantial amounts of sediment that failed and led to the formation and deposition of glacigenic debris flows (e.g. [41, 61, 70]). Furthermore, the study area includes the continental slope off Sjubrebanken, an area that was affected by ice streams prior to ~1.5 Ma, but not or only slightly affected by fast-flowing grounded ice during the last glacials ([39, 41, 51, 61]; Fig. 1). At least 54 gullies intersect the shallowest parts of the study area [19].

The Vestnesa Ridge, a major geomorphological obstacle immediately south of the study area (Fig. 1), has a major influence on the location of the Kongsfjorden Channel System (see below). It is composed of a more than 2-km-thick sediment sequence mainly dominated by contourite drifts (e.g. [7, 23]). However, the upper part of the sediment column on the eastern Vestnesa Ridge is composed of prograding sequences reflecting enhanced sediment supply from Svalbard during glaciations [7].

Vogt et al. [68] presented the location of a section of the 'Kongsfjorden Canyon' immediately north of the Vestnesa Ridge for the first time. Hustoft et al. [24] showed parts of the same system that they named 'Kongsfjorden Channel'. However, we use the term 'Kongsfjorden Channel System' (KCS), because features shown by the authors mentioned above are part of a system, rather than a single channel or a canyon.

Materials and methods

Swath bathymetry and penetration echo sounder data (chirp) provide the basis for this study. The data were collected during cruises of R/V Jan Mayen (now R/V Helmer Hanssen) in the autumns of 2008, 2009 and 2010 [15–17].

The swath bathymetry data were collected with a hull-mounted *Kongsberg Maritime EM 300 multibeam echo sounder* (135 beams, 30 kHz). Sound-velocity profiles for calibrating the instrument were obtained from CTD (conductivity–temperature–depth) casts performed prior to data acquisition. Data processing was performed using the software *Neptune*. However, up to 2.5–4-m-high waves during data acquisition resulted in partly limited data quality. The data are presented at a grid size of 25 m × 25 m and a vertical exaggeration factor of 6 using *Fledermaus*.

The penetration echo sounder data were acquired in 2008 and 2009 with a hull-mounted *EdgeTech 3300-HM* subbottom profiler (chirp; 4*4 array configuration; pulse mode: 1.5–9 kHz, 40 ms). A p-wave velocity of 1500 m/s was applied for depths calculations.

Results and interpretations

Overall bathymetry

Repeated changes in slope gradients characterise the large-scale bathymetry in the study area (Fig. 2). The slope gradient below the shelf break off Sjubrebanken (~250 m) and the Kongsfjorden Trough (~290 m) is up to 20° and 12°, respectively. It decreases to 10°–5° between 400 and ~650 m, to <2° at ~1100 m and towards 0° around 1500 m. Between ~1700 and 2400 m, it increases to 2°–

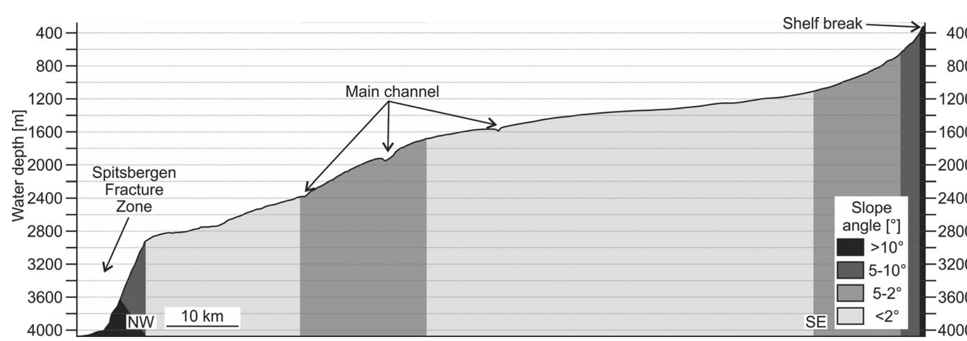

Fig. 2 Downslope profile from the study area showing changes in slope gradients versus water depth. For location, see Fig. 3a

4°, before decreasing again to <2° between ~2400 and 2900 m. Below 2900 m, at the transition into the SFZ, the slope gradient increases to predominantly 5°–20°.

Numerous linear to slightly curved, northward dipping elongated mounds give the seafloor a wavy appearance between ~1400 and 3000 m water depth (Figs. 3, 4e, 5a). These mounds are typically <10 km long, but can occasionally reach 20 km length. They are mostly between 1.5 and 2.5 km wide. Their maximum relief is 20 m.

We interpret these sediment waves as plastered mounded contourite drifts (after [14]) that formed from the northward flow of bottom currents along the eastern slope of the Fram Strait. Similar drifts have been described immediately north of the study area [61], as well as from other places along the continental slope off west Svalbard, e.g. the SE Vestnesa Ridge (1226 m water depth; [23]), the SW Vestnesa Ridge (1500–2500 m water depth; [24]), the western slope of the Yermak Plateau [21], as well as off Isfjorden and Bellsund (1200–800 m water depth; [57]; for locations, see Fig. 1).

An approximately 20-m-high, approximately 2700-m-long, N–S-oriented 'bathymetric step' occurs at ~450 m off Sjubrebanken (Figs. 3, 4a). It is interpreted to be the headwall of a slab failure (compare with, e.g. [3]). Several straight to slightly curved incisions occur on the northernmost parts of the Kongsfjorden TMF and off Sjubrebanken, i.e. on the steepest part of the upper continental slope (Figs. 3, 4a). They are maximum 3000 m long, typically 200–500 m wide and maximum 40 m deep. Their upper limits either terminate some tens of metres below the shelf break or cut back into the shelf. Two of these incisions cut through the headwall of the slab failure. Parallel ridges/raised rims on their sides occur occasionally. Up to 5-m-high depositional features can be observed rarely at the lower ends of these incisions. However, some incisions appear to merge into small channels (see next paragraph). We suggest that these features reflect small-scale retrogressive mass wasting on these steep intervals of the continental slope. Multiple slide scars resulting from large-scale mass wasting occur below 1300–1400 m in the northern part of the study area (Figs. 3, 4e, 5; for details, see [10, 50].

Gullies and small channels

Multiple incisions originate at the shelf break or slightly below on the continental slope off the northern Kongsfjorden Trough (Figs. 3, 4a, 5). They belong to a dendritic network of incisions that expands at least 25 km in N–S direction and ~35 km in E–W direction. These v-shaped, straight to sinuous incisions are up to 5 m deep, typically less than 200 m wide and often only partially visible due to the irregular surrounding relief and the partly limited data quality. However, below 1000 m, maximum 5-m-deep and typically 200–500-m-wide incisions are visible (Figs. 3, 4b, 5). These merge to a single, major incision at 1400 m water depth. The smallest incisions are interpreted to be gullies, whereas the larger ones are small channels (compare with [19, 71]). The small channels located in the subhorizontal interval between ~1150 and 1400 m are the incisions with the highest sinuosity of the entire channel system.

Main channel

One major incision is approximately 60 km long and extends from the lowermost merging point of the smaller channels at 1400 m water depth to approximately 4000 m (Figs. 3, 4, 5, 6). It 'enters' the slide scars described by Osti et al. [50] at 2850 m water depth and 'exits' these again at ~3100 m to continue into the SFZ. This incision is defined as the main channel of the KCS.

The main channel is largest between ~1530 and 2300 m water depth, i.e. in an area of relatively steep slope gradient (compare Figs. 2, 3, 5). There, it reaches a maximum width of 500 m and a depth of up to 80 m. Maximum channel width and depth decrease to 400 and 20 m, respectively, between 2300 and 2680 m water depths. They decrease further to maximum 200 and 5 m between 2680 and 2960 m. At these water depth, the channel occasionally disappears. The reduction in channel size coincides with a decrease in slope gradient. Channel size increases again below 2960 m (i.e. in an area of significant increase in slope gradient) reaching maximum widths and depths of up to 400 and 80 m, respectively.

The channel orientation changes repeatedly. An abrupt change in orientation from a SE–NW to SSW–NNE occurs at ~1575 m water depth. Within the following 4 km in downslope direction, the orientation changes again to SE–NW. It remains constant over approximately 20 km, until c. 2300 m water depth where it changes into a SSE–NNW direction. Within the slide scars, the channel orientation changes from SSE–NNW to E–W, before it enters into SFZ.

Slope angles of the channel sidewalls are up to 30°. Cross section is often slightly asymmetric with the northern wall (right side in downslope direction), being slightly steeper than the southern wall. Minor escarpments of maximum 1000 m width occur on both walls. They are typically more abundant and larger on the northern side.

Several barely visible incisions in the vicinity of the main channel are interpreted to be abandoned and draped channel arms (Figs. 3, 4, 5f). One approximately 1-km-

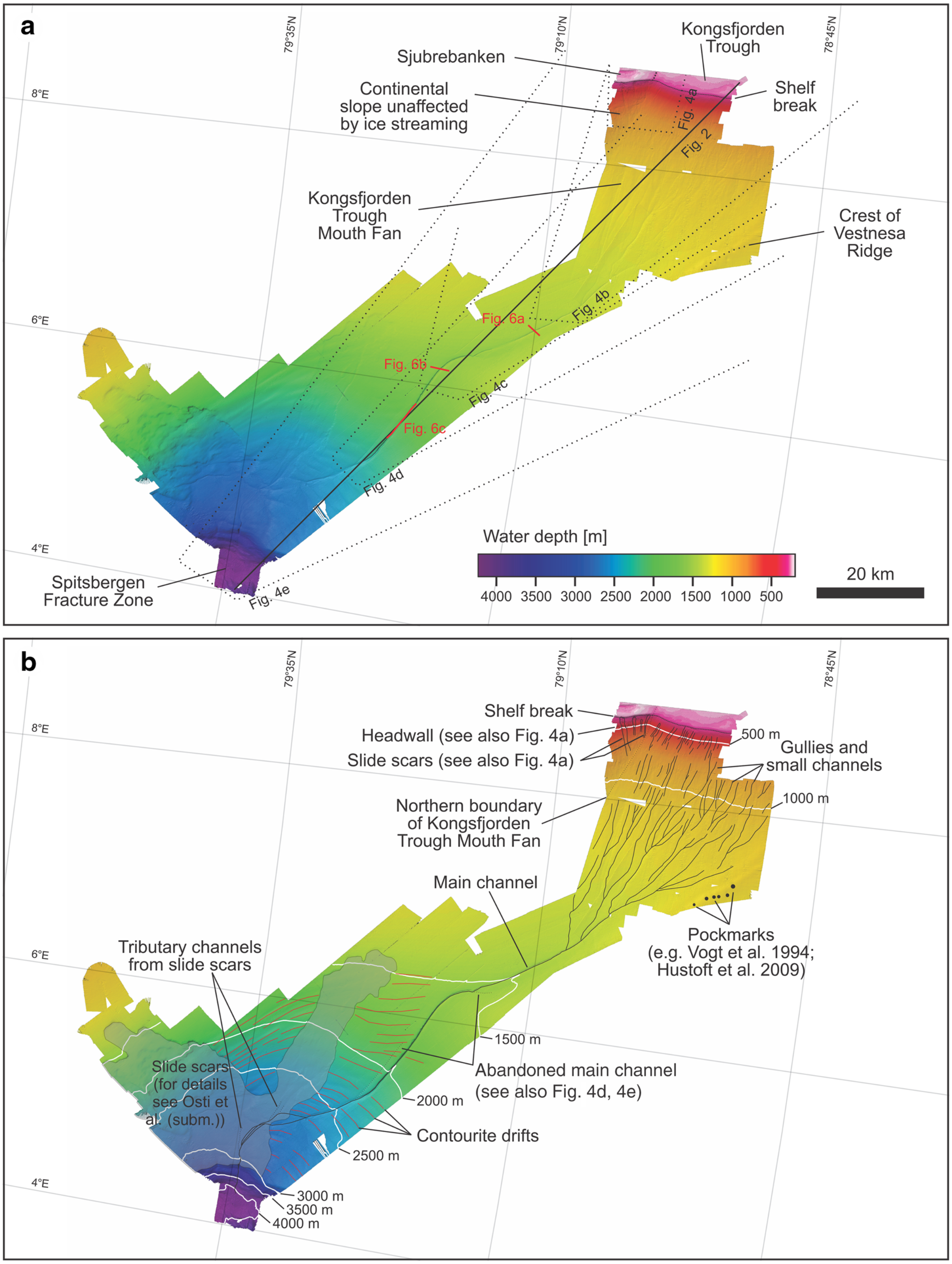

Fig. 3 **a** Swath bathymetry of the study area. Locations of features/landforms mentioned in the text, as well as references to other figures, are indicated. **b** Interpretations of landforms

long, 150-m-wide and 7-m-deep incision merges with the main channel from the SSW at ~1560 m (Fig. 4c). The base of this abandoned channel is approximately 10–15 m shallower than the thalweg and forms a 'hanging valley' at the point of entry into the main channel. Another less well-developed channel appears at ~1800 m water depth

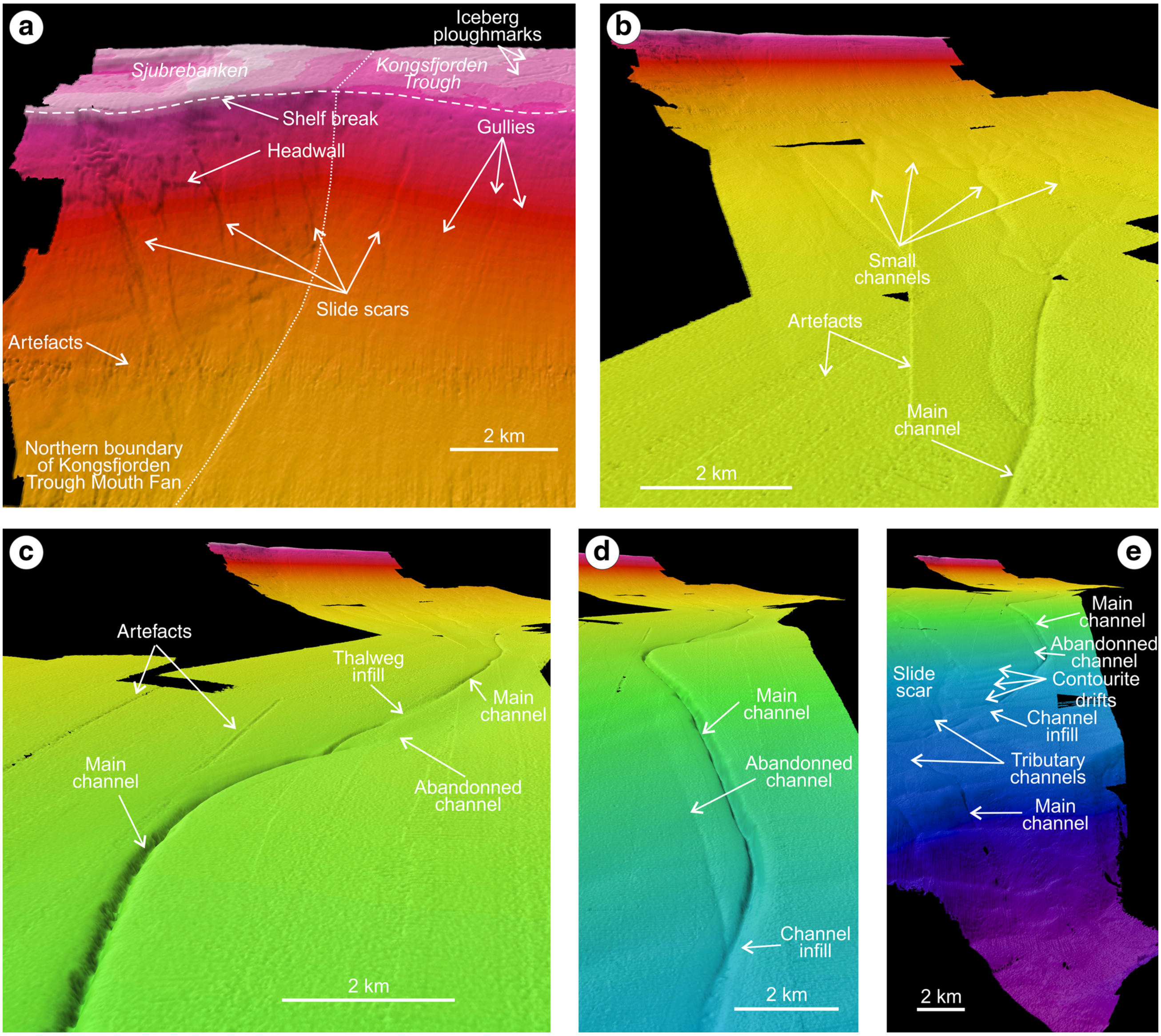

Fig. 4 Zoom-ins of selected parts of the study area. For colour scale, see Fig. 3a. The *slide scar* in **e** is described by Osti et al. [50]

approximately 1.5 km north of the main channel (Fig. 4d). It is less than 10 m deep and maximum 300 m wide. It is oriented subparallel to the main channel and merges with the latter at 2400 m. Well-developed levees, as observed in other channel systems on glaciated continental margins (e.g. [29, 34]), are not present in this setting.

Seismostratigraphy

The uppermost approximately 50 m of the subseafloor area are predominantly acoustically stratified, typically with stratiform reflections (Fig. 6). Spacing between reflections is generally denser within the uppermost 12 m (Fig. 6a) to 15 m (Fig. 6b). The acoustic stratification is suggested to be caused by changes in lithological composition related to variations in bottom-current velocities, transitions between glacials and interglacials and/or very rare overflow from turbidity flows.

Reflections incline towards the channel axis in the uppermost 25 m beneath the seafloor at ~1450 m water depth (Fig. 6a) and 40 m at ~1630 m water depth (Fig. 6b), respectively. As the inclination increases with decreasing depth below the seafloor, we suggest that the channel has been active from its time of formation and until relatively recently (compare with increasing inclination of reflections indicating the recent activity of pockmarks, e.g. [18, 27, 53]).

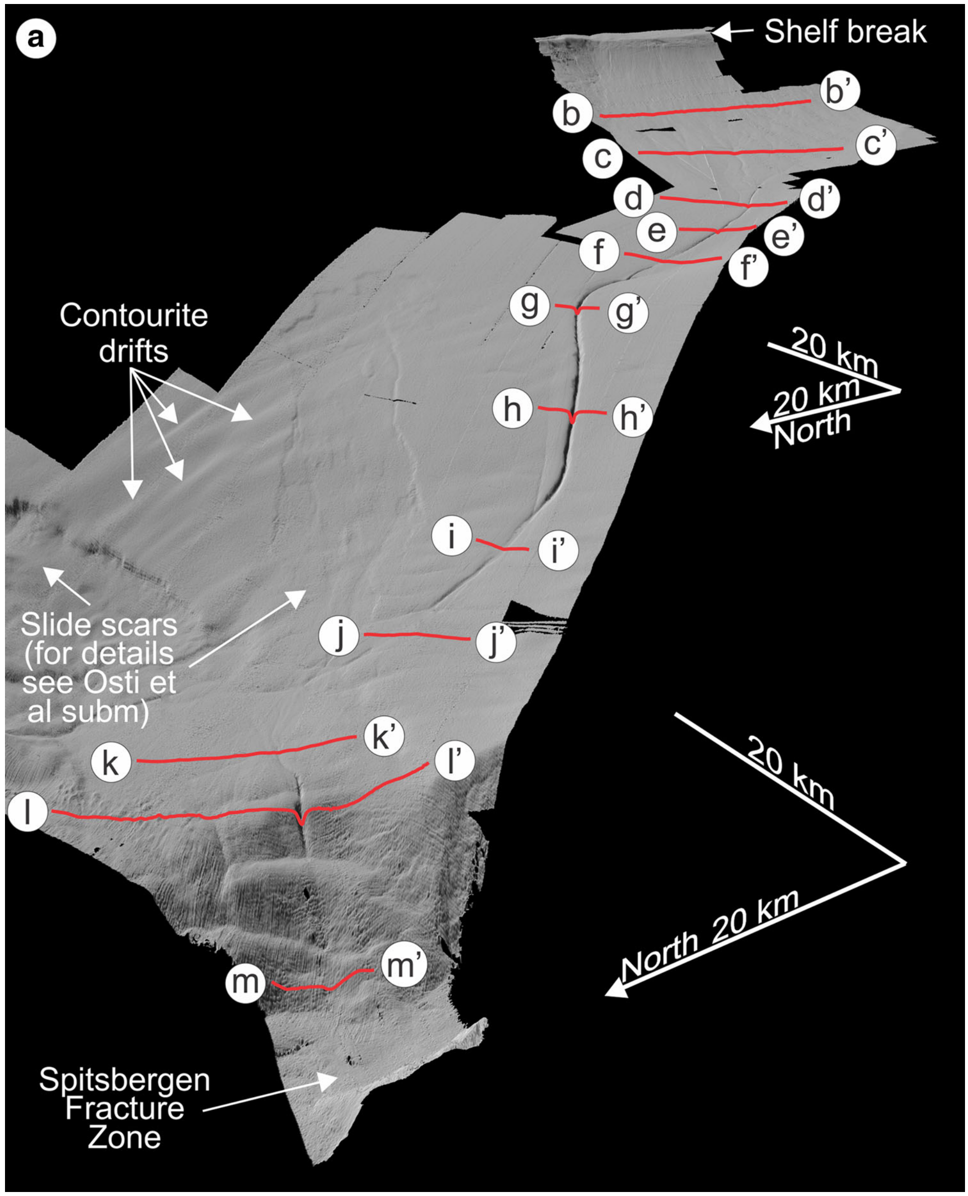

Fig. 5 Cross-profiles along the Kongsfjorden Channel System

Local variations in the overall reflection pattern appear at various water depths, as well as on either side of the channel. Occasional downlap SW of the channel at ~1450 m (Fig. 6a) is probably related to the migration of contourite drifts.

Multiple acoustically transparent bodies with more or less uniform thicknesses of up to 4 m and strong bounding reflections occur 15–25 m below the seafloor (Fig. 6b). These bodies partly truncate underlying acoustically stratified deposits. They are suggested to be overbank deposits originating from overspill or flow-stripping due to the relatively strong curvature of the channel axis from SSW–NNE to SE–NW at ~1575 m water depth (compare with [47, 52, 54]).

Thalweg

The chirp data reveal multiple up to 20–30-m-high obstacles with up to 3 km length along the channel axis between ~1850 and 2400 m water depths, i.e. in a comparatively steep interval of the continental slope (Fig. 6c). Several of these obstacles have a steeper stoss side (upslope) than lee side (downslope). Strong upper-surface reflections are probably caused by a relatively coarse granulometric composition of the thalweg surface due to erosion of fine-grained deposits and/or deposition of coarser grains.

Acoustic stratification occurs within some of the obstacles. Whether or not these internal reflections are

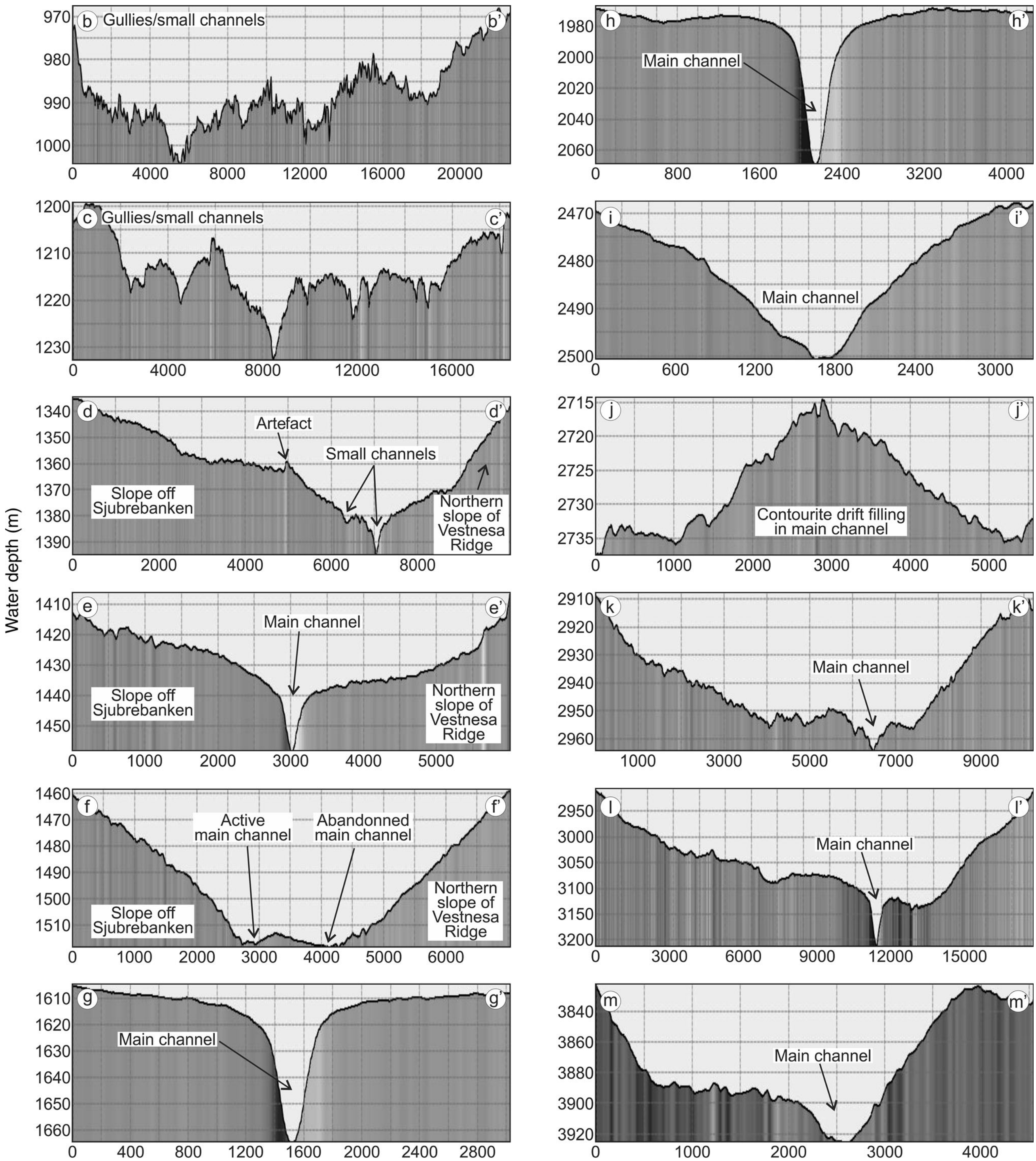

Fig. 5 continued

real or artefacts caused from side reflections cannot be inferred from the available data. However, acoustic stratification beneath the obstacles is assumed to originate from unaffected slope deposits underlying the channel axis.

The occurrence of these obstacles may have multiple explanations. They can be (1) artefacts; (2) mass-transport deposits originating from failure at the channel side; (3) 'original deposits' of limited extent that have not been eroded from bypassing gravity flows.

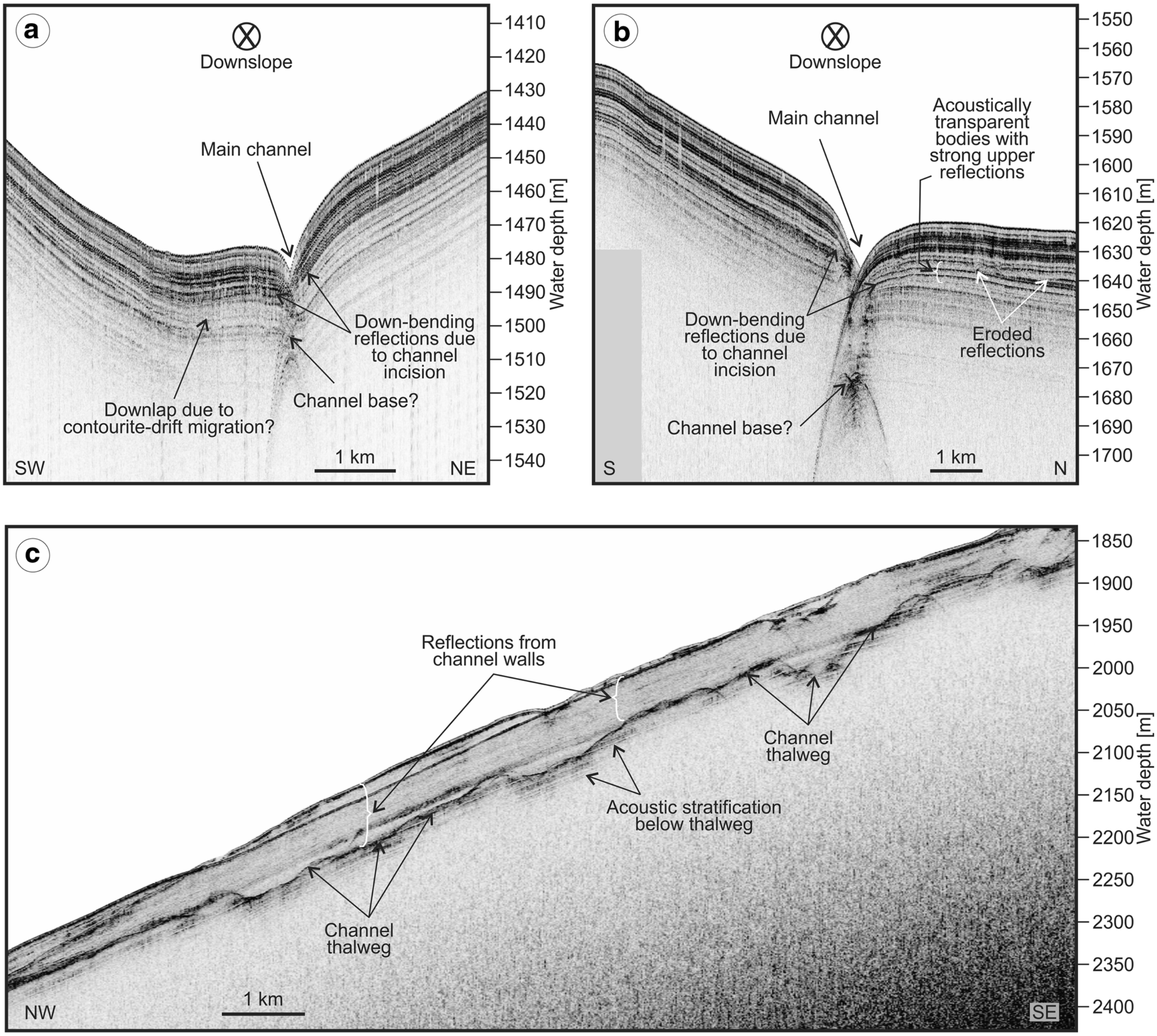

Fig. 6 Penetration echo sounder profiles and interpretations. For locations, see Fig. 3a

Discussion

Geographical constraints on channel location and shape

The regional bathymetry and changes in slope gradients determine the location and shape of the KCS. The relatively straight shape of the gullies in the shallowest part of the study area is probably the result of the steep slope of the Kongsfjorden TMF (Figs. 2, 3, 4a).

The small channels between ~1150 and 1400 m water depths occur in an area with the lowest slope gradients in the entire study area (Figs. 2, 3, 4b) allowing some lateral migration and the development of a partly sinuous shape. However, the slopes of Sjubrebanken and the northern slope of the Vestnesa Ridge 'force' these small channels to merge gradually into the main channel at around 1400 m water depth (Figs. 3, 4b, 5).

The shallowest part of the main channel (below ~1600 m) is relatively straight, even though it occurs within an area of low slope gradient as the sinuous smaller channels at shallower water depth (Figs. 2, 3, 4). This difference is explained by lateral constraints exposed by the slopes off Sjubrebanken and the northern slope of the Vestnesa Ridge, respectively (Fig. 5e, f), preventing lateral migration of the channel.

The main channel has its largest width and depth, as well as the steepest sidewalls, between ~1530 and 2400 m water depth (Figs. 3, 4, 5g, h), i.e. in an area of relatively steep slope gradients (Fig. 2). As laterally constraining slopes are absent (compared to shallower depths), the increase in slope gradient appears to be the main factor forcing the channel to change its direction at ~1575 m water depth and leading to its straight morphology.

Below 2400 m water depth, slope gradients decrease again and the location of the channel appears to be confined by the ambient slopes (Figs. 2, 3, 4, 5i). However, below 2900 m, the marked increase in slope gradient controls the location of the channel and leads to the reestablishment of a wide and deep morphology, similar to between ~1530 and 2400 m.

Age and formation mechanisms

Inclined reflections on chirp profiles acquired from ~1600 m water depth indicate that the channel system has been active during the deposition of approximately 40 m of sediment (Fig. 6b). The establishment of an absolute chronology for the initiation of channel activity remains, however, challenging, because well-dated long sediment records from the study area are not available.

Mattingsdal et al. [41] present seismic data from southern Sjubrebanken. They dated a reflection at 80–100 ms two-way travel time (TWT; <100 m; their 'blue reflection') below the seafloor to ~1.5 Ma. It should be noted that lateral variations in sedimentation rates on glaciated continental margins occur and that sedimentation rates on banks are typically reduced due to winnowing (e.g. [69]. Based on this, we regard 1.5 Ma as a maximum age for channel initiation.

Sarkar et al. [61] present seismic profiles from the vicinity of the chirp profiles presented here. They assign their reflection A3 an age of 0.78 Ma. This reflection appears less than a few tens of milliseconds TWT (<40 m) below the seafloor. Based on this, we infer that the formation of the channel commenced prior to 0.78 Ma. In conclusion, we suggest that channel formation commenced between 1.5 and 0.78 Ma, closer to the latter.

Contourite-drift deposition in the eastern Fram Strait has taken place at least since 11 Ma [7, 41, 61]. The formation of the KCS requires, therefore, a distinct and relatively recent change to enhanced activity of downslope processes.

The first extent of grounded ice streams to the continental margin off northwest Spitsbergen led to the development of the Sjubrebanken Fan from ~2.7 Ma [41, 61]. A major switch in the location of the ice stream to the Kongsfjorden Trough and the formation of the Kongsfjorden TMF occurred around 1.5 Ma [41] or between 1.5 and 0.99 Ma [61].

Since the KCS commences on the Kongsfjorden TMF and since it formed between 1.5 and 0.78 Ma, we suggest that its initiation and activity are mainly related to the advance of grounded ice through the Kongsfjorden Trough to the shelf break. This occurred probably from shortly after 1 Ma, when glacial activity in the Barents Sea region intensified (see [28]).

Sediment sources and sedimentary processes

TMFs are protrusions of the shelves on glaciated continental margins. They formed from repeated slope failure related to the supply of vast amounts of sediment to the shelf break during peak glaciations (e.g. [30, 31, 70, 71]). They can be subdivided into low-gradient and high-gradient TMFs, respectively [60]. Based on Rydningen et al. [60], low-gradient TMFs have surface inclinations of 0.5°–1.0°, whereas the surfaces of high-gradient TMFs typically have slope angles of 1°–15°. Thus, the Kongsfjorden TMF, having slope angles up to 12°, can be defined as a high-gradient TMF. It formed during multiple glaciations, including the last glacial, when fast-flowing, grounded ice reached the shelf break off northwest Spitsbergen repeatedly [38–41, 51, 61, 70, 71].

The KCS originates at the shelf break of the Kongsfjorden Trough, where multiple gullies provide evidence of small-scale erosion into the continental slope, as observed in other Arctic channel systems (e.g. [8, 19, 71]). Gully formation has probably mainly taken place during glaciations when grounded ice reached the mouth of the Kongsfjorden Trough. Various mechanisms may have led to their formation, including descending dense water masses rejected from brine formation, turbidity flows beyond the mouths of glacial troughs or retrogressive slope failure (compare with [8, 19, 43, 48, 60, 71]). Sediment supply into the gully system may also have occurred during interglacials, due to winnowing of fine-grained material from the upper parts of the continental slope (compare, e.g. with [2, 60]). However, sediment flux has most probably been significantly lower compared to glacials.

Sakar et al. [61] suggest that the Kongsfjorden TMF is composed of debris flows. However, our bathymetry data do not reveal any evidence of debris-flow lobes as extensive and voluminous as observed on low-angle TMFs (compare, e.g. with [30, 31, 71]). This may indicate that (1) debris flows forming beyond the Kongsfjorden Trough were generally small and/or (2) debris flows originating at the shelf break, or slightly below, detached from the seafloor on the steep upper slope of the Kongsfjorden TMF and travelled through the KCS by hydroplaning (compare with, e.g. [32]) and/or (3) debris flows transformed and disintegrated into turbidity flows (compare with, e.g. [9, 60]).

The absence of depositional features/intervals within the channel(s) suggests that sediments are evacuated from/ 'flushed out' of the active system. Furthermore, the absence of well-developed levee systems indicates that turbidity flows were generally small and confined to the channels.

Multiple minor escarpments along the steep sidewalls of the main channel provide evidence of repeated slope failure and 'internal' sediment supply to the system. The failures can have resulted from oversteepening and failure of these up to 30° steep walls or from undercutting of the northern slopes (note the partly asymmetric cross-profile of the main channel, e.g. Fig. 5h; compare with [44]). As the study area is located close to the SFZ, we also regard the release of tectonic stress (compare with [55]) as a potential trigger for failures on the sidewalls. The failed material was either immediately evacuated or subsequently eroded by subsequent gravity flows.

The comparatively deep and wide incision of the channel between ~1530 and 2300 m and below 2960 m suggests that the erosive behaviour of focused downslope processes exceeds along-slope processes in steeper areas of the continental slope (Figs. 2, 4, 5). However, in less inclined areas, e.g. around 1500 m and between 2680 and 2960 m, the channel is partly to entirely filled (Figs. 4d, 5j). We suggest that these infills are composed of contourite drifts, rather than being deposited from decelerating turbidity/debris flows. We assume that the turbidity/debris flows (1) have a state of hydroplaning allowing them to cross these areas without (or only with minor) erosion (compare with [11, 32, 45]) and/or (2) travel around the contourite drifts before being 'forced back' into the main channel by the overall topography in the area.

Comparison of high-latitude channel systems

Channel systems on and off glaciated continental margins are prominent features of various sizes and configurations occurring at a wide range of water depths. Their activity was maintained by a variety of downslope processes transferring sediment from the shelf break/upper continental slope to the deep sea. As the activity often correlates with glacial activity, some channel systems can provide valuable archives to study the dynamics of past ice sheets. A summary of various properties/characteristics of selected channel systems in the Arctic and Antarctica is presented in Table 1 and discussed below.

Whereas other channel systems extend over several hundreds of kilometres and onto extensive abyssal plains continuing off the respective continental slopes, the maximum possible extent of the KCS is constrained by the shelf break and the SFZ. As a consequence, the KCS is, with its 120 km length, one of the shortest systems (Table 1). However, even though it is comparatively short, it covers the largest depth range (250–4000 m water depth). Furthermore, it crosses submarine slopes with the largest variety of inclinations compared to the other systems (0°–20°). Being maximum 500 m wide, the KCS is typically at least one order of magnitude narrower than other channels that can reach widths of up to 20 km. However, despite this, it belongs to the deeper channel systems (Table 1). The deepest incisions occur in areas with the steepest slope gradients allowing the gravity flows to accelerate and erode deeper into the subseafloor than in less-steep inclined areas.

The overall location of the largest channel systems is controlled by the general increase in water depth without any influence of lateral obstacles allowing lateral migration occasionally over tens of kilometres (NP-28; Table 1). However, the orientation of smaller systems is often controlled by other factors including bordering by TMFs (e.g. INBIS Channel), canyon walls (Central Scotian Slope), sediment drifts (North Antarctic Peninsula) or the ambient large-scale bathymetry which, in case of the KCS, is defined by the slopes off Sjubrebanken and the Vestnesa Ridge. Thus, these smaller systems remain often laterally relatively stable.

Channel systems on glaciated continental margins originate mostly in the continuations of glacial troughs that formed when fast-flowing grounded ice streams transport vast amounts of sediment to the shelf break during repeated glaciations (Table 1). These ice streams acted often as sources for processes leading to incision and channel formation (see below). However, occasionally, channel formation is pre-defined by the existence of large canyons (e.g. Lofoten Basin Channel, Central Scotian Slope).

The oldest channel systems formed around 2.5 Ma (off East Greenland, NP-28; Table 1), i.e. the systems formed after the onset of enhanced northern hemisphere glaciations. The systems were typically most active during peak glaciation when ice streams reached their maximum extents, delivering extensive amounts of sediment to the shelf break and the heads of the channel systems. Failure of these sediments led to the formation of debris and/or turbidity flows. However, turbidity flows could also originate directly from hyperpycnal flows of cold and sediment–laden glacial meltwater at the ice margin or from brine rejection during the formation of sea ice during periods, when grounded ice did not extend to the shelf break. Furthermore, sediment supply could also occur from failure along canyon/channel walls (Central Scotian Slope, North Antarctic Peninsula, KCS), as well as from winnowing (Lofoten Basin Channel, KCS) during glacials and interglacials.

The dominant agent maintaining high-latitude channel systems is turbidity flows (Table 1). These flows can move

Table 1 Properties/characteristics of selected channel systems at high latitudes

	Lofoten Basin Channel	INBIS	Four channel systems off East Greenland	NP-28	Central Scotian Slope	North Antarctic Peninsula	Kongsfjorden Channel System
Parameter							
Position	~69°–69°30′ N; ~7°–16° E	~74°-75° N; ~10°-15° E	~73°–75°30′ N; ~4°–16° W	~84°-90° N; ~60° W–0°–45° E	~42°30′–43°30′ N; ~59°30′–61°30′ W	~63°–65°30′ S; ~63°–72° W	~78°50′–79°50′ N; ~4°–9° E
Location	Lofoten Basin	Greenland Basin, off western Barents Sea	Greenland Basin	Amundsen Basin, Arctic Ocean	Off East Canada	west of Antarctic Peninsula	Eastern Fram Strait, off NW Spitsbergen
Length (km)	~200	60	Up to 300	At least ~400, presumably ~650	Some tens of km	Up to ~150	~120
Water depth (m)	~2200–3200	2360–2520	~1500–3800	~1000–4000	900/1200–3000	2800/2900–~3800	~250–4000
Width (km)	<3	5–15	2–10	Up to 20	0.1	>8	0.2–0.5
Channel depth (m)	<30	50–60	<100	Up to >200	10	Up to >200	5–80
Slope angle	N/A	N/A	<1°	N/A	2°–4°	Up to 18°	0°–20°
Shape/orientation/constraining factors/borders	Single channel; Curved: SE–NW–NE–SW–SE–NW; Turning towards deepest part of basin; Northern border: Bear Island TMF	Single channel; E–W; bordered by Storfjorden and Bear Island TMFs	Four, generally SE–NW-oriented channel systems; Low sinuosity; Turning north, towards deepest part of basin; becoming braided in deepest and gentlest areas	Subparallel to Lomonosov Ridge; At least four relict channel positions within uppermost ~400 m of sediment column; Migration of 50 km of parts of channel towards Lomonosov Ridge	Generally NNW–SSE; Determined by canyon walls/sides	SE–NW; Confined between up to 500–1000-m-high mounds (sediment drifts); No significant lateral migration of systems	Overall SE–NW with modifications; Influenced by surrounding large-scale morphology and slope gradients; Main channel deepest and widest in areas with high slope gradients
Sedimentary processes	Turbidity flows	Turbidity flows	Turbidity flows	Turbidity flows	Turbidity flows; debris flows	Translation from debris flows to turbidity flows; Turbidity flows are main components leading to formation of canyon–channel systems	Debris and turbidity flows; Eventually hydroplaning debris flows
Sediment sources	Failure at the margin of grounded ice at shelf edge; Failures within Andøya Canyon; Winnowing on continental shelf	Turbidity flows and debris flows originating from the Storfjorden and Bear Island TMFs, as well as interfan area of Kveitehola Trough	Turbidity flows beyond the mouths of glacial troughs; Hyperpycnal flows; Retrogressive slope failure	Tributary channels off North Greenland and North Canada (Lincoln Sea)	Turbidity flows: failure of proglacial sediments in canyon heads or direct hyperpycnal flows from subglacial meltwater at the ice margin; Holocene turbidity flows: suspension on the shelf during storms; Debris flows: at canyon heads (close to shelf break) and canyon walls	Failure at the margin of grounded ice during glacials; Slope failures on mounds can supply sediment to canyon–channel system	Failure at margin of Kongsfjorden ice stream; Retrogressive slope failure; Hyperpycnal flows; Failures on sidewalls of main channel

Table 1 continued

	Lofoten Basin Channel	INBIS	Four channel systems off East Greenland	NP-28	Central Scotian Slope	North Antarctic Peninsula	Kongsfjorden Channel System
Age/period of activity	Mainly during glacials; Significantly less during Holocene	Mainly during glacials; Significantly less during Holocene	Repeatedly since ~2.5 Ma; Prior to c. 13,000 cal. BP; Mainly during glacials	After 2.5 Ma; Maximum input and activity during glacials	Uncommon during Holocene; Strong correlation between glacial advances and failures	Mainly during glacials (supply from grounded ice), but also during interglacials (slope failures on mound slopes)	Since ~1 Ma; Mainly during glacials and probably during interglacials
«Other» e.g. levee, depositional lobe	Continuation of Andøya Canyon; Poorly developed levees; >25-m-thick turbidity flows; Sandy lobe at mouth	Upper part buried under debris flows; 10–15-m-high levee on northern flank; Mud waves north of the levee—>frequent overflow; Thicker sediment deposits in northern side of channel; >50-km-wide Inbis Fan at mouth	Continuation of Kejser Franz Josef Trough; Tributary system at shallow water depth; Levees on eastern side; Sandy depositional lobes (3000–5000 km^2)	Single large channel within a channel system on North Pole Submarine Fan; Channel–levee complexes; Higher levees on eastern side; Dividing into two smaller channels in eastern Amundsen Basin; Overbank deposition from turbidity flows	Originate within canyons (canyon floors); Central channels or broad, flat-channel floor; Up to 50-m-thick debris-flow deposits filling canyon floors; Turbidity flows can be confined and unconfined; Holocene turbidity flows: probably restricted to the thalweg	Dendritic pattern with varying numbers of tributaries; Distributions of troughs and banks influenced the location of canyon-channel systems; No apparent link between canyon-channel system and glacial troughs on shelf at present; Hydraulic jump from 18° to 4° degrees at the foot of the slope → formation of suspension clouds carried away by bottom currents	Asymmetric cross section of main channel; Gullies, small channels and main channel; Gullies originating at shelf break; Partly infilled with contourites; Overall contouritic setting; Termination in Spitsbergen Fracture Zone; Depositional lobe(s) and levees absent
Data base							
Swath bathymetry	X		X		X	X	X
Seismics reflection/ penetration echo sounder	X	X	X	X	X	X	X
Side-scan sonar	X	X	X				
Sediment cores	X	X	X	X	X		
References	[2, 9, 35, 37, 71]	[71]	[8, 43, 48, 49, 71, 73]	[29]	[44]	[1, 56]	This study

as confined flows over several hundreds of kilometres often leading to the deposition of extensive sandy lobes beyond the channel mouths. However, lobe deposition at the mouth of the KCS is absent, because the SFZ prevents flows from spreading out laterally. This leads to aggradation, rather than progradation beyond the termination of the system. Turbidity flows can occasionally also spread out beyond the lateral limits of the channels. This occurs, e.g. in the form of overflows leading to the formation of poorly to well-developed levees and overbank deposits (see examples from the Atlantic and Arctic Oceans), but it can also be related to hydraulic jumps due to marked changes in slope gradients at the foot of the slope (North Antarctic Peninsula).

It has also been suggested that debris flows can play a certain role in channel development. The deposits of debris flows can either fill the canyon floor (Central Scotian Slope), the flows can disintegrate into turbidity flows (e.g. North Antarctic Peninsula), or they might pass through the system by hydroplaning (KCS).

Conclusions

Swath bathymetry and penetration echo sounder data have been analysed to investigate the morphology, processes and time of activity of the KCS on the continental slope off northwest Svalbard. The main conclusions are:

- The KCS is located in a contouritic setting between the mouth of the Kongsfjorden Trough and the Spitsbergen Fracture Zone where slope gradients vary between $\sim 0°$ and 20°. It is approximately 120 km long and ranges from ~ 250 to 4000 m water depth. It includes multiple gullies on the Kongsfjorden TMF, as well as few incisions resulting from slope failures, merging to small channels that further merge to a main channel. Maximum channel width and depth are 500 and 80 m, respectively.
- The location and orientation of the channel system are controlled by the ambient regional bathymetry and variations in slope gradients.
- The system has probably been active since ~ 1 Ma, when glacial activity increased and grounded ice repeatedly expanded to the shelf break to form the Kongsfjorden TMF. The system was presumably most active during glacials when grounded ice delivered high amounts of sediment to the shelf break by grounded ice, leading to slope failures and the formation of debris flows and/or turbidity flows. However, some—though significantly reduced—activities may have occurred during interglacials.
- The absence of well-developed channel–levee complexes indicates that turbidity currents were relatively small and confined, and that overspill is absent or occurred rarely.
- The absence of large debris-flow lobes may indicate that debris flows originating off the Kongsfjorden Trough during the last glacial were generally small. Furthermore, debris flows either presumably disintegrated into turbidity flows or travelled through the system by hydroplaning.
- Whereas the main channel is deeply incised and void of any deposits along the thalweg in the steeper parts of the continental slope, contourite drifts partly fill the channel in areas with gentler gradients. The absence of erosion in these parts may reflect that the downslope moving flows cross the areas of infill by hydroplaning or that they move around the elevations before being forced back into the main channel.
- The main differences of the KCS compared to other channel systems on glaciated continental margins are that it is relatively short, covers a large range of water depth on a relatively steep slope and is that the main channel relatively deep compared to its width.
- The results of this and other studies show that submarine channel systems at high latitudes can provide valuable tools for the reconstruction of past ice-sheet dynamics.

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