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Quaternary contourite drifts of the Western Spitsbergen margin

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ABSTRACT

The study of contourite drifts is an increasingly used tool for understanding the climate history of the oceans. In this paper we analyse two contourite drifts along the continental margin west of Spitsbergen, just south of the Fram Strait where significant water mass exchanges impact the Arctic climate. We detail the internal geometry and the morphologic characteristics of the two drifts on the base of multichannel seismic reflection data, sub-bottom profiles and bathymetry. These mounded features, that we propose to name Isfjorden and Bellsund drifts, are located on the continental slope between 1200 and 1800 m depth, whereas the upper slope is characterized by reduced- or non-deposition. The more distinct Isfjorden Drift is about 25 km wide and 45 km long, and over 200 ms TWT thick. We revise the 13 years-long time series of velocity, temperature, and salinity obtained from a mooring array across the Fram Strait. Two distinct current cores are visible in the long-term average. The shallower current core has an average northward velocity of about 20 cm/s, while the deeper bottom current core at about 1450 m depth has an average northward velocity of about 9 cm/s. We consider Norwegian Sea Deep Water episodically ventilated by relatively dense and turbid shelf water from the Barents Sea responsible for the accumulation of the contourites. The onset of the drift growth west of Spitsbergen is inferred to be about 1.3 Ma and related to the Early Pleistocene glacial expansion recorded in the area. The lack of mounded contouritic deposits on the continental slope of the Storfjorden is related to consecutive erosion by glacigenic debris flows. The Isfjorden and Bellsund drifts are inferred to contain the record of the regional palaeoceanography and glacial history and may constitute an excellent target of future scientific drilling.

1. Introduction

The study of contourite drifts is valuable as a proxy for the climate history of the oceans since these sedimentary deposits typically form along the pathways of major bottom currents (Laberg et al., 2005; Rebesco et al., 2008). They have relatively high and continuous accumulation rates in contrast to adjacent condensed pelagic sequences (Knutz, 2008). Contourite drifts are well-known throughout the world oceans, occurring anywhere from the abyssal floor to outer shelf settings, and particularly along the continental slope where bottom currents are confined by the Coriolis effect (Faugères and Stow, 2008).

Although they show a large morphological variability, most drifts have an elongated, mounded shape and variable dimensions, ranging from small patch drifts (about 100 km^2) to giant elongated drifts (> 100,000 km^2). Contourite drifts are tens to hundreds of km long and from 10 to more than 100 km wide, with sediment thicknesses from some tens to more than 1000 m. Their body is generally elongated, more or less parallel to the continental margin and hence to the contour-current flow direction. Erosion

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and non-deposition are dominant near the current axis, while deposition occurs further away where the velocity is lower (Faugères and Stow, 2008).

The Fram Strait (Fig. 1) is the only deep opening through which water masses are exchanged between the Nordic Seas and the Arctic Ocean. Atlantic water is advected northward through the eastern Fram Strait in the West Spitsbergen Current. This warm water keeps the large areas west and north of Svalbard (increasingly larger due to present warming) nearly ice-free in winter and thus has implications for the Arctic climate (IPCC, 2007). It is hence of climatologic interest to know how this flow has changed during geological time scales.

Bottom currents have been shown by Eiken and Hinz (1993) to have influenced the sedimentation in the Fram Strait since the Late Miocene. Their study was based on contourites identified west of the Svalbard Archipelago with multichannel seismic profiles from the seventies and eighties, and a correlation to DSDP site 344. More recently, the identification of mounded seismic patterns in the Early Pleistocene sediments off Bellsund Fan (Fig. 2) and on the Vestnesa Ridge (Fig. 1) led Amundsen et al. (2011), Sarkar et al. (2011) to infer that contour-controlled currents on the Svalbard margin were effectively influencing the sedimentation during that period.

In this paper we show two contourite drifts along the continental margin west of the Svalbard Archipelago between 76–78°N. We illustrate their geometry and facies on seismic reflection data directly correlated to ODP Site 986 and their location and extension on bathymetric data. The flow structure and properties of water masses in the area are shown based on oceanographic data including hydrographic sections and a 13 year long time series from moored instruments. The time series displays a local near-bottom velocity maximum in close proximity to the contourites. The aim of this paper is to explain the growth of these contourite drifts in the light of modern oceanography and discuss the palaeoceanographic changes that may be inferred from the seismostratigraphic evidence.

2. Methods

Acquisition of seismic and geologic data (Fig. 2) was performed during the EGLACOM cruise (R/V OGS-Explora, summer 2008) and the SVAIS cruise (R/V Hesperides, summer 2007) contributing to IPY Activity 367 NICE-STREAMS (Neogene ice streams and sedimentary processes on high-latitude continental margin). The seismic gear included a 1200 m long digital streamer with 96 channels (spaced 12.5 m) and a 160 cubic inches array of sleeve guns. Fold coverage was 24, shot interval 25 m and sampling rate 1 ms. The processing included a *t*-squared scaling for spherical divergence correction, MCS spiking deconvolution, bandpass filtering varying with the water bottom and trace equalisation. For sub-bottom profiling, the hull-mounted Benthos CAP-6600 sub-bottom chirp profiler was used. Gravity cores were analysed through an X-ray CT-scan, visually logged, photographed, scanned with a GEOTEK multi-sensor core logger (MSCL). Water content, grain size, biostratigraphic and clay mineral content were investigated along with AMS14 C dating on foraminiferal tests and continuous palaeomagnetic and rock magnetic measurements. Finally, an integrated interpretation of all data has been performed using the Kingdom Suite software provided by Seismic Micro-Technology.

Multibeam echosounder data were acquired in 2006 and 2007 by the scientific team of the R/V "Akademik Nikolaj Strakhov" that belongs to Geological Institute RAS with financial support of Russian Academy of Science and Norwegian Petroleum Directorate. The 12 kHz RESON SeaBat 7150 multibeam echosounder system generates 234 beams with focused beamwidth $2^\circ \times 2^\circ$ (swath coverage 150°). Horizontal datum was WGS84 for the survey. The current sea level was used for vertical datum. The raw data were processed onboard using PDS2000 software. As a result, the digital terrain model was created with a 200 m isometric grid resolution. Finally, the data have been low-pass filtered and superposed to the IBCAO bathymetry (Jakobsson et al., 2012).

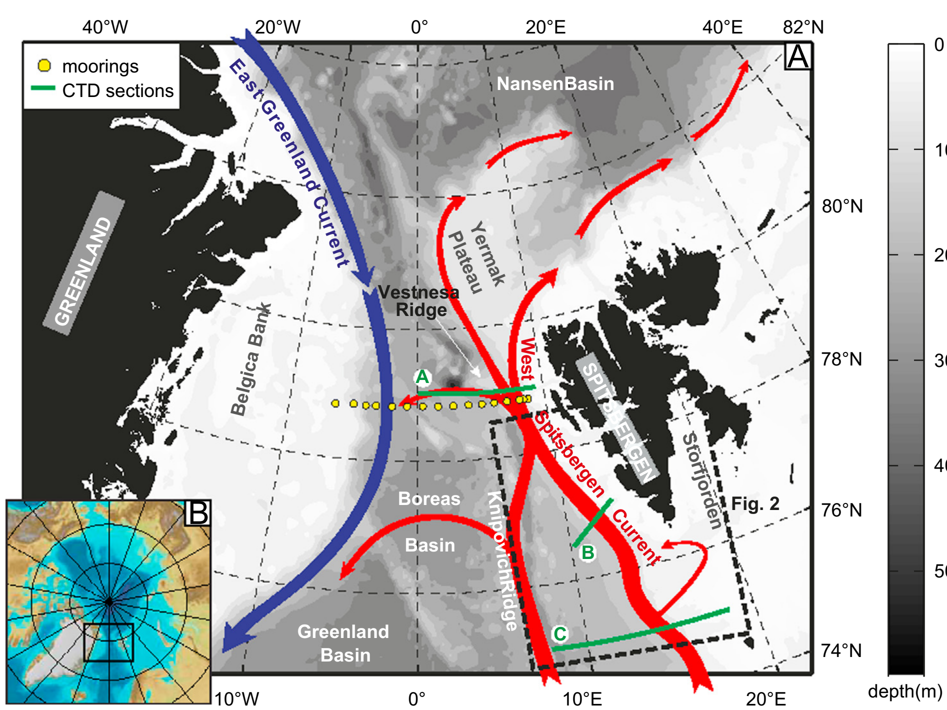

Fig. 1. Location Map. (A) Bathymetry of the region showing the main currents, the position of the moorings (yellow dots) and the three sections in Fig. 3 (green lines). The dashed square indicates the region covered by Fig. 2. (B) Location of (A) within the Arctic Ocean (from Jakobsson et al., 2012). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

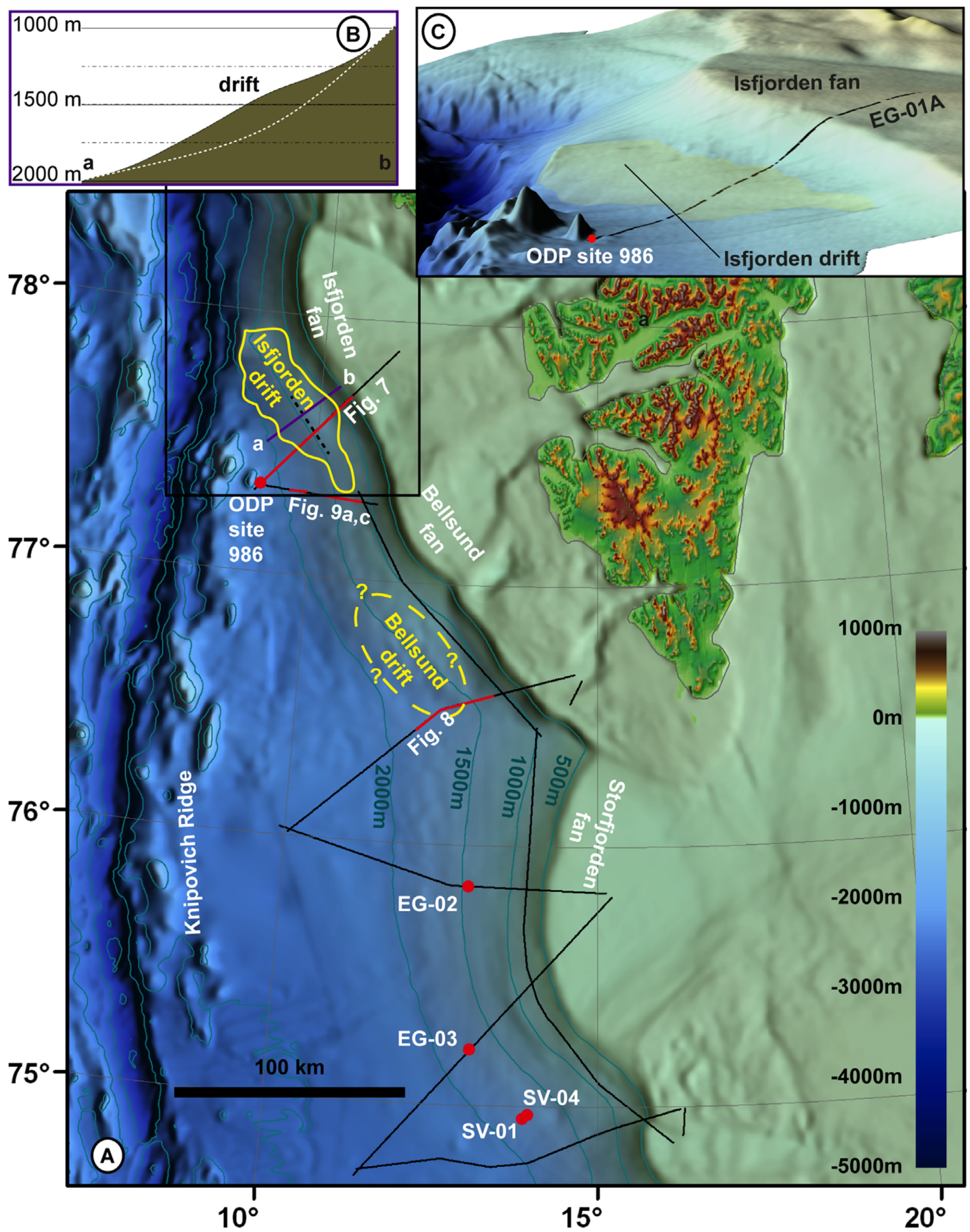

Fig. 2. Areal extension of the contourite drifts. For location see Fig. 1. (A) Bathymetry map showing the extension of the drifts and the position of the shown seismic profiles. The position of the bathymetric profile a–b of inset B is also shown. Light Parameters: Altitude 75°, Azimuth100, Vertical Exaggeration 10. (B) Bathymetric profile a–b across the Isfjorden Drift. (C) 3D perspective of the Isfjorden Fan and the Isfjorden drift, the latter visible as a gentle bump in the morphology of the middle slope (highlighted in yellow). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

An array of 14 to 16 deep oceanographic moorings has been maintained for 13 years at 78°50'N covering the Fram Strait from the shelf west of Svalbard to the eastern Greenland shelf (Fig. 1). The horizontal resolution ranges from 10 km at the upper slope to 30 km in the deep area. Velocity, temperature and, at some locations, salinity was measured at standard levels: ca. 50 m; 250 m; 750 m; 1500 m; and 10 m above the bottom. Each level was instrumented with rotor or acoustic current meters from Aanderaa Instruments (RCM7, RCM8, and RCM11) or from Falmouth Scientific Inc (3D -ACM), and temperature and salinity sensors from Sea-Bird Electronics Inc. (SBE37 and SBE16). The current and temperature data were collected at 1- or 2-h intervals, despiked, low-pass filtered with a cut-off period of 40 h to remove a tidal signal, and averaged over 6-h intervals. Detailed description of data accuracy and processing can be found in Fahrbach et al. (2001) and Schauer et al. (2004). CTD profiles (Fig. 3) have been taken with a Neil Brown Mark III b CTD system, which carried also a transmissometer.

3. Oceanography

3.1. The West Spitsbergen current in Fram Strait

Previous investigations (e.g. Aagaard et al., 1973; Jonsson et al., 1992) have detailed a continuous inflow of warm and saline Atlantic-derived water to the Arctic on the eastern side of the Fram Strait (Fig. 3), steered by the continental slope as is common for large-scale ocean currents due to Earth's rotation (e.g. Gill, 1982). In the western Fram Strait, Arctic water and recirculating Atlantic Water are flowing southward. The currents in the eastern part have a strong barotropic component indicating that they are

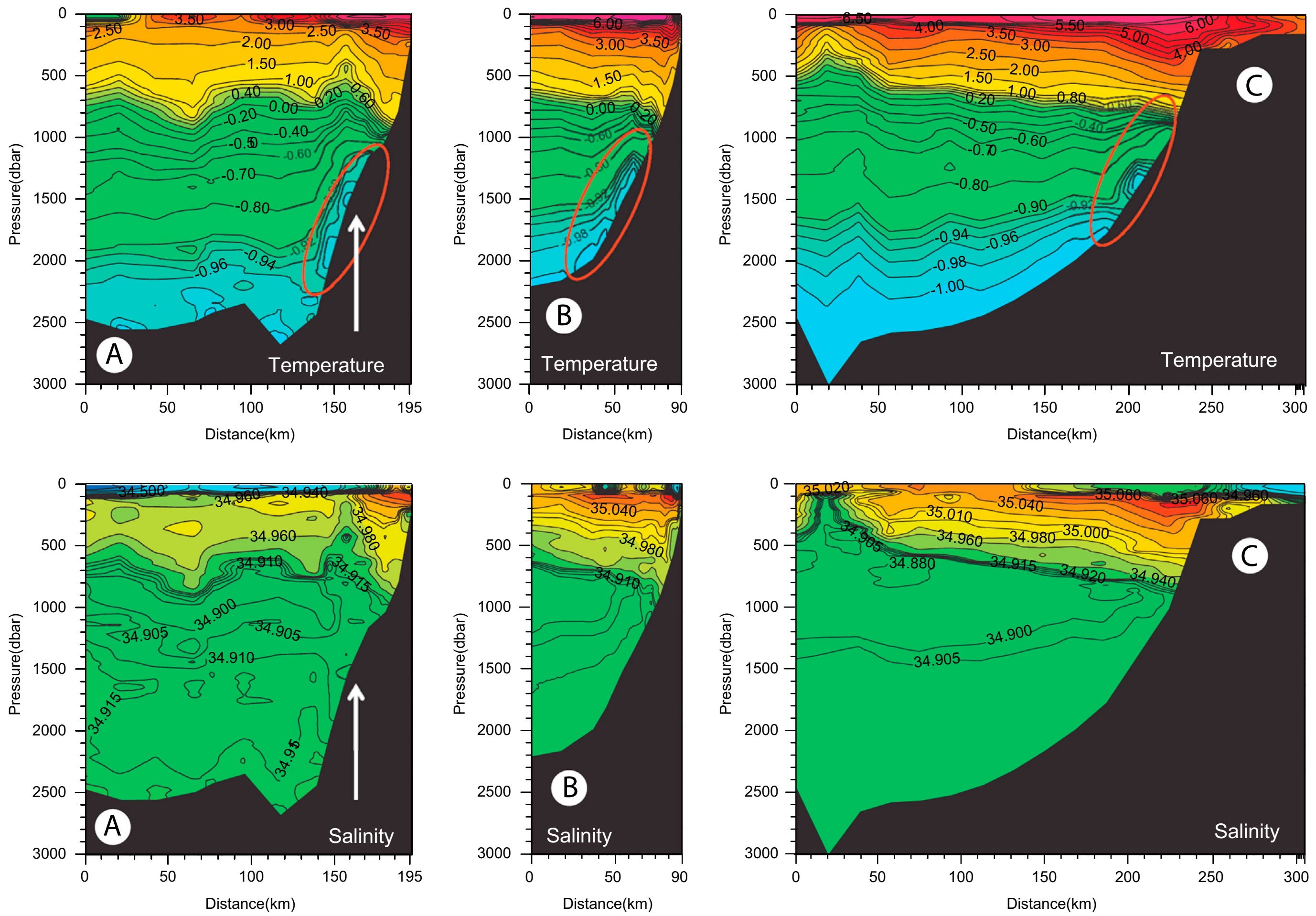

Fig. 3. Cross-slope sections of temperature and salinity during 1998. (A) Fram Strait; (B) slope region west of Spitsbergen; (C) slope region South of Spitsbergen. The white arrows in (B) indicate 7°E, i.e. the approximate location of the intensified bottom current visible in the long-term velocity average (Fig. 4). Red circles indicate the part of the current that leans on the slope and flows Northward due to geostrophy. For location of the sections see Fig. 1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

driven primarily by the wind field. The strongest and most persistent flow takes place at the upper slope west of Spitsbergen and is called the West Spitsbergen Current (WSC). The temperature of the WSC is variable due to atmospheric conditions. The Atlantic core can be 2–4 degrees with salinities between 35.1 and 35.3 (Aagaard et al., 1987). The currents are highly fluctuating on a sub-annual time scale (e.g. Jonsson et al., 1992; Teigen et al., 2011), but the yearly average is fairly constant (Beszczynska-Möller et al., 2012).

Beszczynska-Möller et al., 2012 analysed a 13 year long time series of velocity, temperature and salinity obtained from a mooring array maintained across the Fram Strait since 1997 (Fahrbach et al., 2001). They confirmed the strong barotropic velocity structure (Fig. 4) with a mostly unidirectional northwards flow from top to bottom and northwards over the entire eastern slope. Yet there is a baroclinic shear associated with the Atlantic layer temperature maximum so that the highest record-averaged velocities of more than 20 cm/s occur near the surface. Besides the surface velocity maximum, there is also a deep increase of the velocity at 7°E at a bathymetric depth of ca. 1420 m which is likely induced by the baroclinic pressure gradient from the dense water leaning on the slope there (Fig. 3). The meridional velocity measured in the mooring at this position 10 m above seabed (Figs. 5 and 4) has an average value of 8.5 ± 0.2 cm/s and a an intensification of the flow up to 30 cm/s is often observed in late winter/early spring (Fig. 5). This near-bottom baroclinic core at 7°E is characterized by a higher mean velocity as compared to two adjacent moorings located up- and downslope with mean near-bottom velocities of 5.6 ± 0.2 and 4.2 ± 0.2 cm/s, respectively. The baroclinic deep core also has higher directional stability than the near-bottom flow observed at adjacent moorings. It is proposed that the observed enhanced stratification is created by dense shelf water plumes from the large shelf region further east.

3.2. Origin of the bottom water at the Fram Strait slope

Fig. 3 shows that below a salinity minimum around 1000 m depth the lower continental slope west of the north-western Barents Sea and Svalbard is covered by cold (< -0.9 °C) and slightly more saline (> 34.91) water. The properties of this water match those of Norwegian Sea Deep Water (NSDW), which flows northward in the deep WSC (Aagaard et al., 1985; Rudels et al., 2000; Langehaug and Falck, 2012). However, this deep-water flow may episodically be ventilated by relatively dense shelf water. Such dense water is produced in winter through persistent freezing and brine release in the polynyas of the Barents Sea, particularly in the Storfjorden (Quadfasel et al., 1988; Schauer, 1995) or at the central Bank (Quadfasel et al., 1992). On the shelf, the plumes are characterized by near bottom layers of low temperature, homogenized by bottom boundary turbulence (Schauer and Fahrbach, 1999). They proceed towards the shelf edge and, depending on their density and on the relative importance of bottom friction (Price and O'Neil Baringer, 1994; Wåhlin and Walin, 2001; Borenäs et al., 2002) flow down the continental

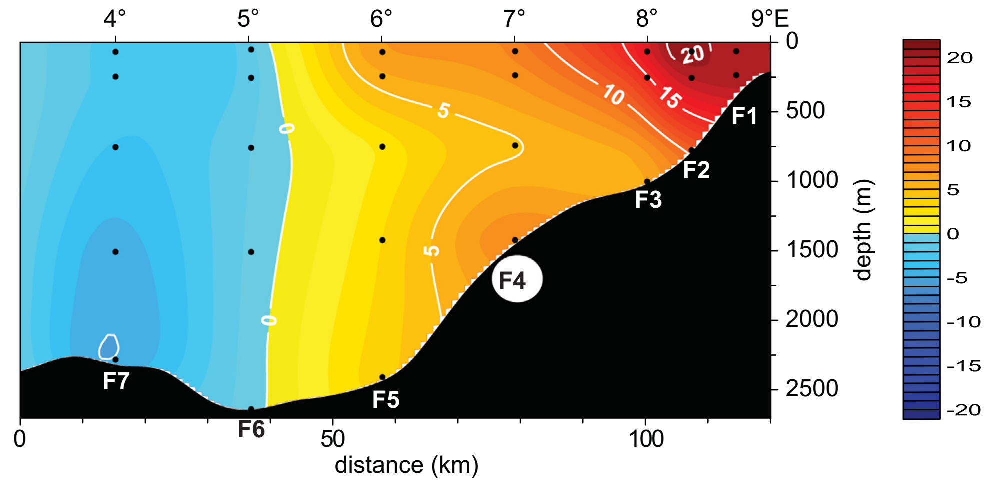

Fig. 4. Cross-strait section of long-term mean (2002–2008) current velocity measured at the eastern part of moored array indicated in Fig. 1 (modified from Beszczynska-Möller et al., 2012). The mooring F4 shown in Fig. 5 is highlighted.

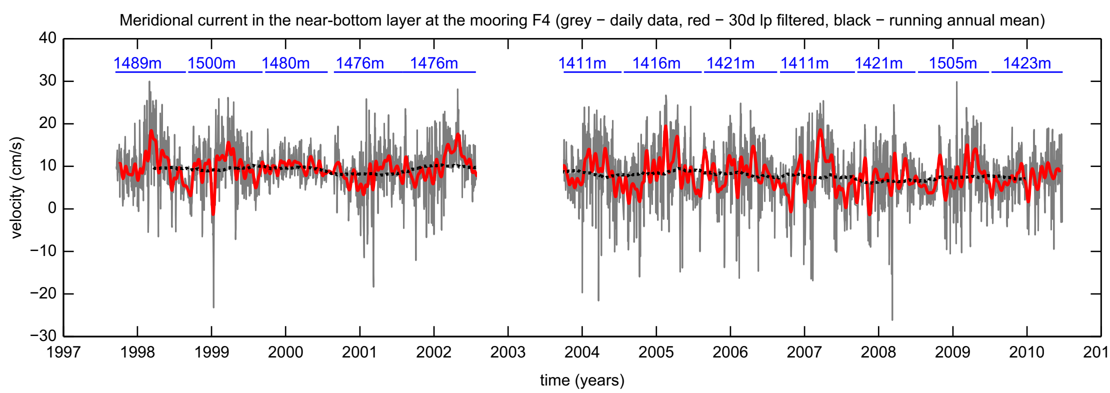

Fig. 5. Bottom velocity at mooring F4 (Beszczynska-Möller et al., 2012). For location see Fig. 4.

slope thereby entraining ambient water, which means here entrainment of warm and saline Atlantic Water. As a result, Arctic shelf water plumes penetrating below the Atlantic layer carry a warm signature (Quadfasel et al., 1988; Rudels, 1995; Akimova et al., 2011).

However, not in every year the shelf water plumes are large or saline enough to provide water to the deep Fram Strait (Skogseth et al., 2007) and due to their sporadic nature and small scale, dense water plumes are not easy to detect. In 2002, a dense water plume passed the mooring at 7°E at 1476 m water depth, identified by elevated temperatures for several months. The flow during that time showed less fluctuations and the bottom average velocity was increased from 8 cm/s to 12 cm/s (Akimova et al., 2011).

The shelf water plumes often show elevated levels of turbidity indicating that the high velocities associated with the plumes create enough turbulence to erode sediments or prevent sedimentation. Fig. 6 shows an example of these sediment-laden cold shelf waters. This indicates the possibility of further densification of these plumes due to suspended matter. Honjo et al. (1988) found in sediment traps moored over a year close to the bottom in the north-eastern Norwegian Sea a strong peak of sedimentation in winter over five months. The material was lithogenic, contrary to the summer maxima of biogenic origin. This observation is in very good accordance with the explanation that dense shelf water plumes erode shelf material and provide it to the deep Fram Strait.

At least part of the modern circulation described here has prevailed in previous geologic times. Atlantic water has been present on the southwestern Svalbard margin in the last tens of thousand years (extending down to 1485 m during the Last Glacial Maximum) despite extensive sea ice covers and enhanced inputs of meltwater from the south (Rasmussen et al., 2007). A meridional current system similar to the present-day one, with inflow of temperate waters from the south and large areas of seasonally open waters providing moisture for ice sheet growth during glacial stages (Hebbeln et al., 1998) has persisted through the last hundred thousand years with varying strength and intensity.

4. Contourite drifts

4.1. Seismic geometry and morphologic expression

A series of seafloor undulations are visible on the seismic profiles crossing the mid continental slope west of Spitsbergen (Fig. 2). These undulations consist of a broad upward-convex body (mound) whereas the upper slope shallower than about 1200 m depth is characterized by reduced- or non-deposition (Figs. 7–9). The mounds extend for a few tens of km in the dip direction (perpendicular to the shelf edge). They are either without any further deeper depression (Fig. 7), with a change to different seismic facies (Fig. 8) or with a slight downward curvature (Fig. 9). The relief of the mounds is less than 100 m. The length of these features in the strike direction (parallel to the shelf edge) cannot be verified directly within our seismic grid that has a distance between the survey lines in the order of several tens of km. Moreover, the extension of the mounds are hard to detect on the bathymetric map (Fig. 2). The northern one was within the multibeam survey conducted by the R/V Akademik Nikolaj Strakhov, while for the southern one no multibeam bathymetric data are available. The northern mound (Fig. 2), visible on the map as a subtle shadow, is about 30 km wide and 70 km long. It is located offshore of the Isfjorden Fan and is sub-parallel to the continental slope at a distance of about 10–15 km from the shelf edge.

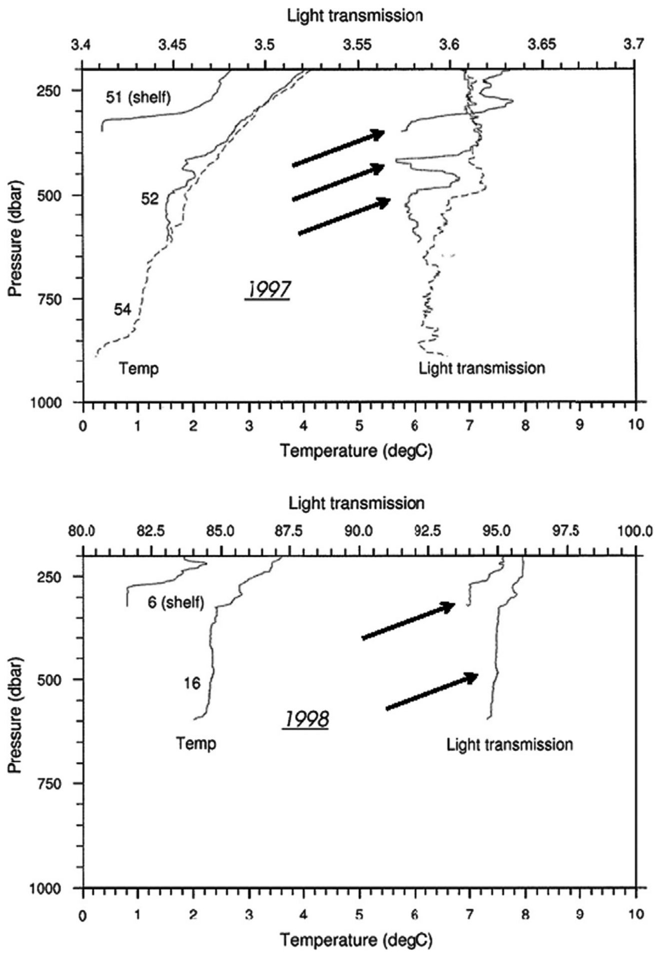

Fig. 6. Light transmission and temperature from the dense shelf water in Storfjorden in 1997 and 1998. Arrows indicate water masses where turbidity is high and temperature is low.

The mounds are composed of thick sedimentary accumulations showing laterally continuous, medium-high amplitude upslope-migrating sigmoidal reflectors. The lateral continuity is much higher than that of the adjacent deposits that are found upslope (Fig. 7), downslope (Fig. 8) and buried below the mound (Fig. 9). Amplitudes are generally higher than those of the adjacent deposits and are particularly high on the upward side of the mounds. The adjacent deposits may also have very high amplitudes (Fig. 8), but these alternate with very low amplitude (almost transparent) lensoidal facies. The thickness of the mound, greater than 200 ms TWT at the top (Figs. 7 and 8), is gradually decreasing downslope. Conversely, upslope of the top its thickness is decreasing significantly over short distances. Where thickness decreases to less than 1/4 over distances of few km (Fig. 7) the termination of the drift is more distinct. Where it decreases to less than 1/2 over distances of up to 10 km (Fig. 8) the termination is less clearly defined. The sigmoidal geometry of the mound is complicated by the existence of minor undulations. Where upward thickness decrease is less rapid there is a greater number of minor undulations (2 in Fig. 8 compared to 1 in Fig. 7). The characteristics of the two mounds are summarized in Table 1.

The upward termination of the drifts appears to be produced by progressive thinning and systematic onlap termination of the reflectors, with the upper slope characterized by non-deposition (by-pass) or reduced deposition rather than by erosion. Onlap is more pronounced where upward thickness decrease is more rapid. The termination of the onlapping reflectors is not even or linear. The geometry of the reflectors passes from upward convex beneath the top to upward concave on the upslope side of the mounds (Fig. 7). This upward concavity apparently migrated progressively upslope along with the top of the mound and the zone of onlap termination. The presence of a mounded sigmoidal geometry of the reflectors and the seismic facies help identifying the onset of the mound growth that we infer synchronous with reflector R4A (Figs. 7 and 8). Beneath reflector R4A the mounded geometry is not detectable and the sedimentary sequences are steadily downslope thinning.

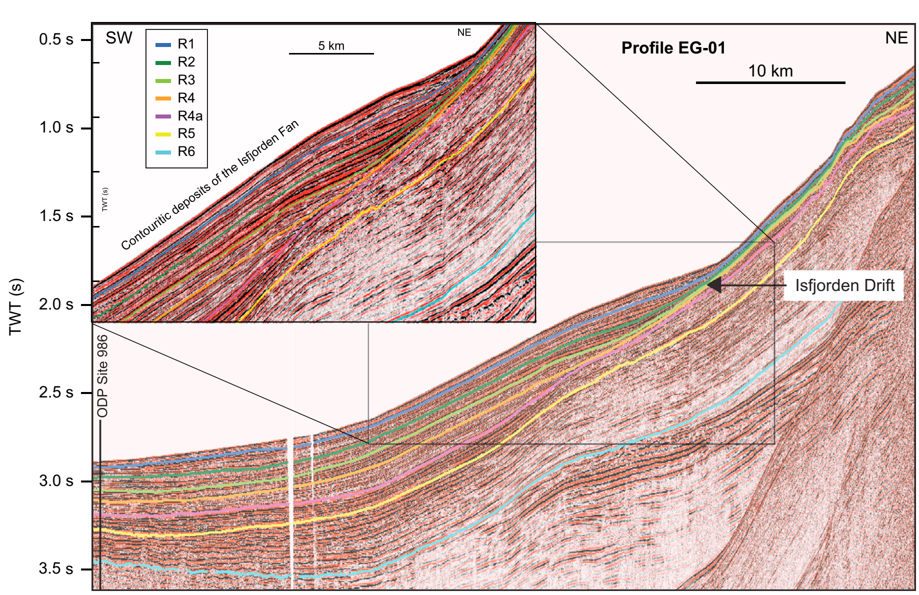

Fig. 7. Multichannel seismic profile EG_01A crossing the Isfjorden Drift. For location see Fig. 2.

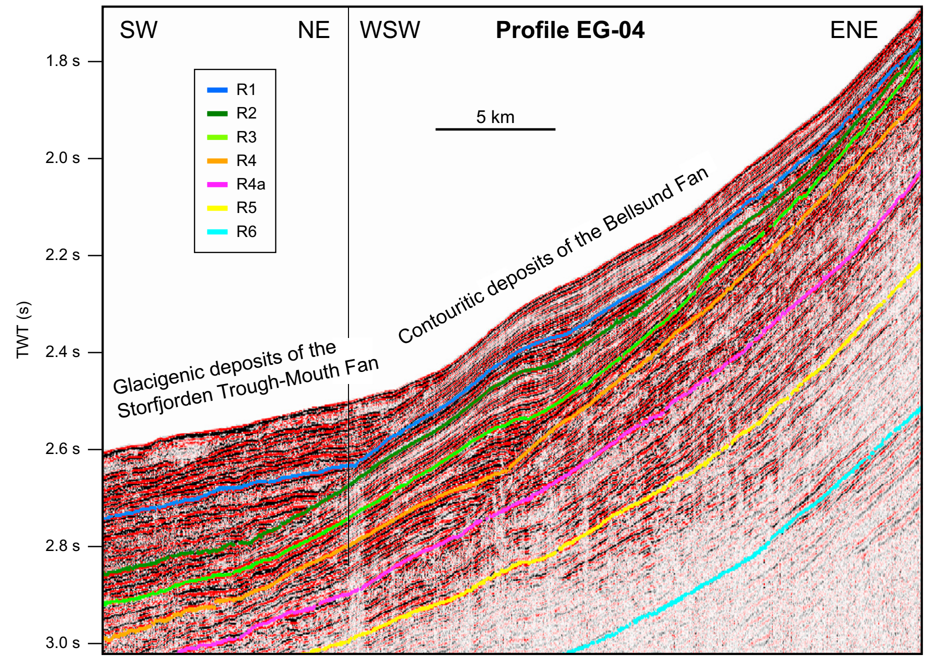

Fig. 8. Multichannel seismic profile EG_04 crossing the Bellsund Drift. For location see Fig. 2.

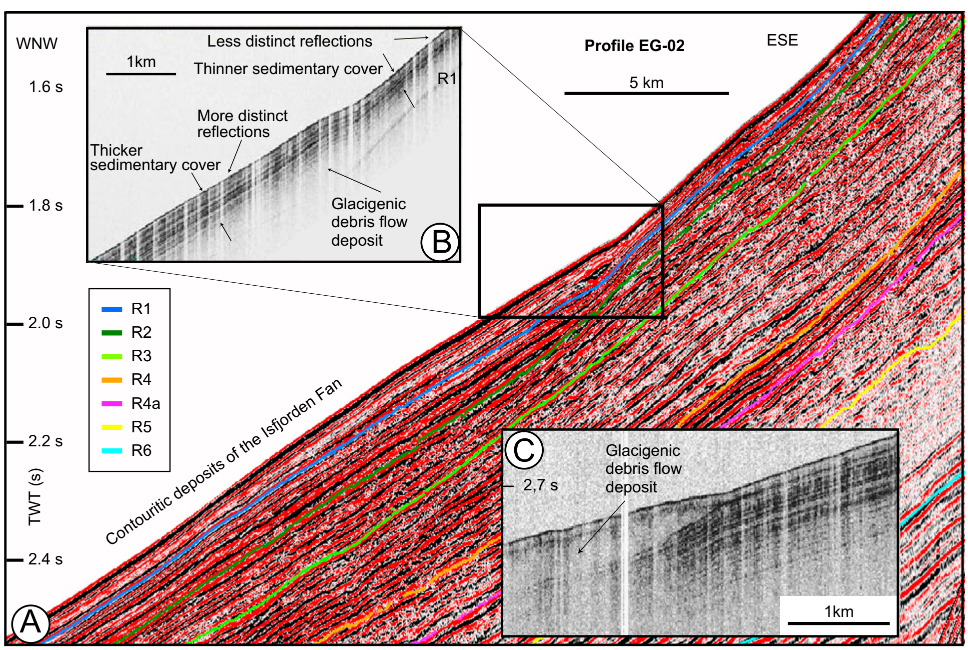

Fig. 9. Seismic image of the southern tip of the Isfjorden Drift. (a) Multichannel seismic profile EG_02A. (b) CHIRP sub-bottom profile crossing the upward termination of the southern tip of the Isfjorden Drift. (c) CHIRP sub-bottom profile along the distal part of the seismic profile EG_02A showing intercalated contourites and transparent glacigenic lenses. For location see Fig. 2.

4.2. Chronology of the seismic reflectors

An upper regional unconformity defines the base of the glacigenic sediments on the continental shelf (Solheim and Kristoffersen, 1984; Vorren and Kristoffersen, 1986; Solheim et al., 1996). Towards the shelf break, where the glacigenic succession increases in thickness, several unconformities occur. The most pronounced unconformities correspond to reflectors R7, R5, and R1, which define the boundaries between the three main seismic units GI, GII, and GIII (Faleide et al., 1996), corresponding to units TeC, TeD, and TeE of Vorren et al. (1991).

Site 986 of ODP Leg 162 drilled this succession in a distal position offshore western Svalbard (Raymo et al., 1999). The various dating methods applied gave somewhat conflicting results and because of this, Reflector R7 was given a tentative age of 2.3–2.4 Ma. No definite age could be assigned to R5 but linear interpolation indicated an age of about 1.3 Ma. The same approach for R1 gave an age estimate of 0.2–0.44 Ma (Forsberg et al., 1999).

A re-evaluation of the biostratigraphy of Site 986 led Knies et al. (2009) to suggest additional biostratigraphic datums of ~2.41 Ma at ~649 mbsf and ~2.76 Ma at ~900 mbsf. They also found that the base of Hole 986D dates to ~3.2 Ma. From this, Knies et al. (2009) revised the age of R7 to ~2.7 Ma.

In this study we follow Knies et al. (2009) and use the age of ~2.7 Ma for Reflector R7. For R5 and R1 we slightly revise the tentative ages of Forsberg et al. (1999) using linear interpolation

Table 1
Characteristics of the sediment mounds.

Northern mound (Isfjorden drift)	Southern mound (Bellsund drift)
About 30 km wide	?
About 70 km long	?
About 10–15 km from the shelf edge	About 10–15 km from the shelf edge
About 1100–1900 m depth	About 1200–1800 m depth
Relief < 100 m	Relief < 100 m
Thickness about 200 ms	Thickness about 200 ms
Thinning to < 1/4 in few km on upper side	Thinning to < 1/2 in about 10 km on upper side
Distinct upslope termination	Undefined upslope termination
More pronounced onlap	Minor onlap
One minor undulation	Two minor undulations

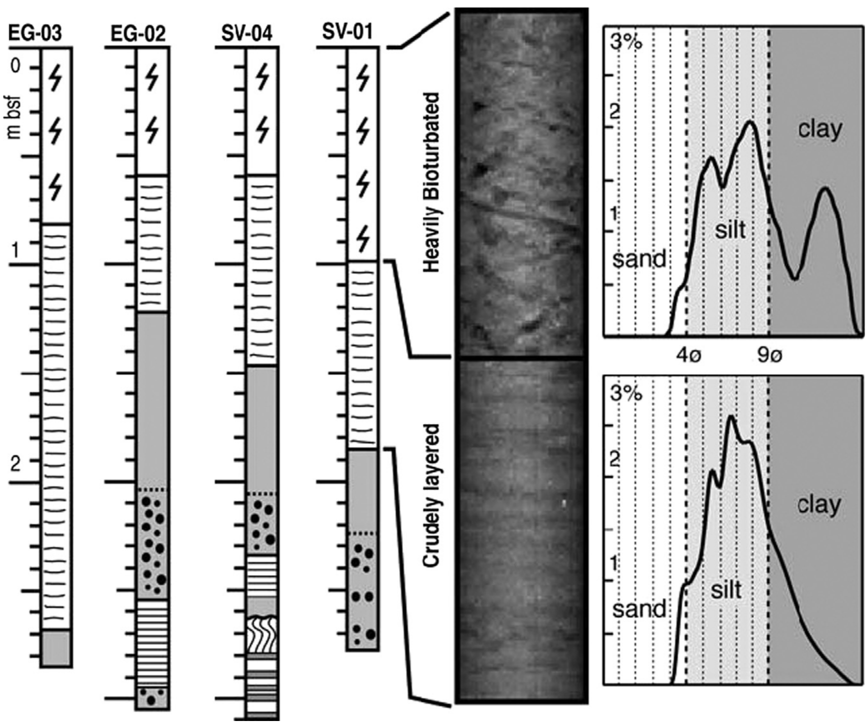

Fig. 10. Logs of the core sediments from the Storfjorden Trough Mouth Fan (EG-02 and EG-03 from EGLACOM Cruise and SV01 and SV-04 from SVAIS Cruise). X-radiographs of the two uppermost lithofacies are indicated together with the correspondent grain size spectra of distribution. Core Location in Fig. 2.

between the new datums at ~649 and ~900 mbsf from Knies et al. (2009), and the Brunhes/Matuyama boundary at 133 mbsf and the top of the Jaramillo Subchron at 152 mbsf (Channell et al., 1999). Based on this approach the R6, R5, R4A, R4 and R2 are given tentative ages of about 2.1, 1.5, 1.3, 1.1 and 0.4 Ma, respectively. Reflector R1 is assigned an age of about 0.2 Ma.

4.3. Sediment cores on the mid slope of the Storfjorden Fan

We collected sediment cores only in the Storfjorden area (Lucchi et al., in press). The uppermost 1–2 m of the cores on the mid continental slope (1400–1800 m water depth, cores SVAIS-1, -4 and EG-2, -3) is composed by two facies: crudely layered and heavily bioturbated (Fig. 10). Both lithofacies are characterized by low-density (1.4–1.6 wet bulk density), high water content (up to 60% wet weight) and fine grained sediments (averages of 5% sand, 65% silt and 30% clay). The diatoms-bearing crudely layered sediments are characterized by unimodal spectra of grain size distribution that, together with crude bedding, suggest deposition under almost undisturbed traction currents with little bioturbation mostly visible through radiographs. The bioturbation progressively increases upward to become pervasive in the uppermost foraminifera-rich, heavily bioturbated facies. Silty mottles and large burrows completely obliterated the primary depositional structure as indicated also by polymodal grain size spectra (Fig. 10).

5. Discussion

5.1. Interpretation of the sediment mounds

The seismic expression of the two sediment mounds identified on the mid continental slope west of Spitsbergen is common to that of many contourite drifts (Faugères et al., 1999; Rebesco and Stow, 2001; Stow et al., 2002; Rebesco, 2005; Rebesco et al., 2008; Hernández Molina et al., 2011a) including previously described drifts in the Norwegian-Greenland Sea (Laberg et al., 1999, 2002). In fact, both mounds are distinctly upward convex and there is some morphologic evidence that at least the northern one (that we name Isfjorden Drift for its vicinity to the Isfjorden trough) is along-slope elongated. No direct morphologic evidence exists for the southern one (that we name Bellsund Drift for its vicinity to the Bellsund trough), but an along-slope elongation is consistent with the geometry observed on the seismic profile EG-04 (Fig. 8). Like many other mounded, along-slope elongated drifts (see e.g. Faugères and Stow, 2008), they have dimensions of some tens of km with length/

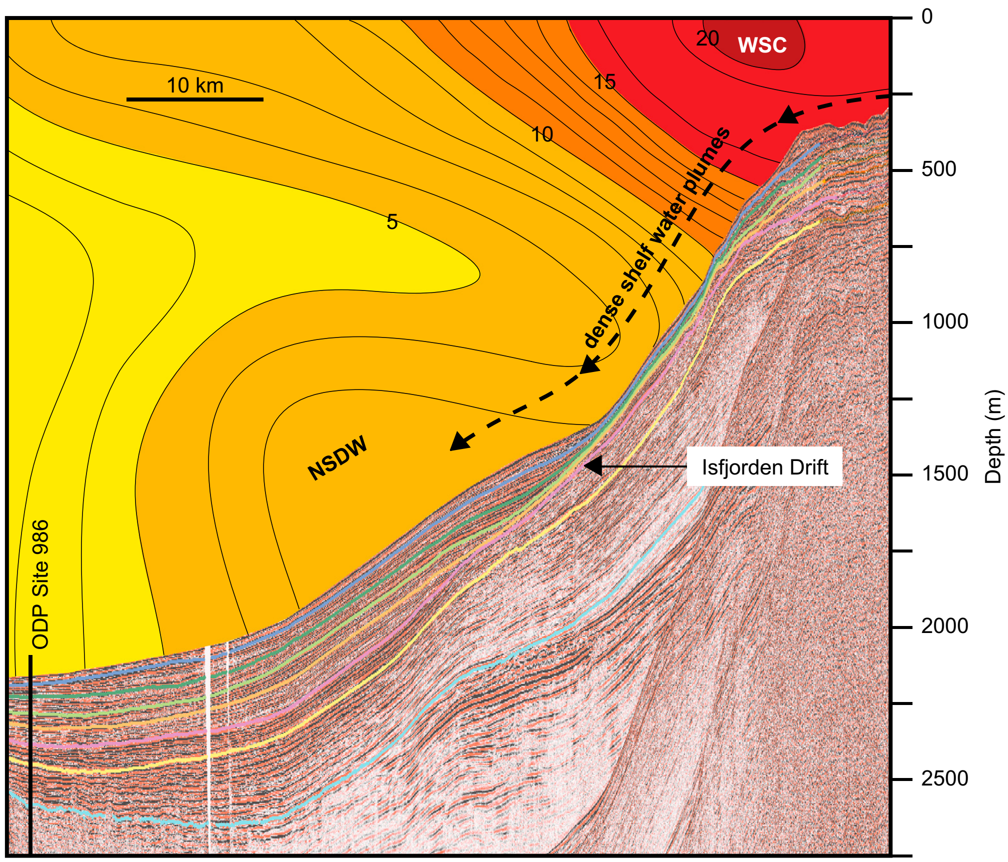

Fig. 11. Summary figure showing the relationship between the long-term current regime and the sub-bottom sediment geometry. The upper part (current regime) is freely redrawn on the basis of the velocity section along the moored array at about 78°50′ shown in Fig. 4. The lower part (sediment geometry) is taken from the multichannel seismic profile EG_01A crossing the Isfjorden Drift (shown in Fig. 7) south of 77°30′. The vertical scale of the seismics has been converted in depth using the conventional 1500 m/s sound velocity in water. This conceptual diagram helps to portray the mechanism responsible for the accumulation of contourites: sediment delivery beneath the local maximum of the northward bottom flow of Norwegian Sea Deep Water (NSDW) episodically fed by dense shelf water plumes. Conversely, reduced deposition occurs beneath the high-velocity West Spitsbergen Current (WSC) shallow core. The black numbers refer to current velocity (cm/s).

width ratio of about 2:1, thickness of few hundreds of metres and an up-slope lateral migration marked by oblique/sigmoidal reflector pattern in seismic lines.

According to the shown seismic characteristics, the sediment mounds identified on the mid continental slope west of Spitsbergen can be classified as slope plastered contourite drifts. These drifts are indeed very similar to other examples of plastered drifts, such as that on the Hebrides slope, adjacent to the Wyville Thomson Ridge (Howe et al., 1994; Stoker, 1998; Stoker et al., 1998), that on the North-eastern Chatham rise (Wood and Davy, 1994), the Gardar drift (Kidd and Hill, 1986) and the Lofoten Drift on the Norwegian continental slope (Laberg et al., 1999). Moreover, these drifts have the typical dimensions of medium-size plastered drifts: 10^3–10^4 km^2 (Faugères et al., 1999).

These plastered drifts west of Spitsbergen generate a kind of seaward-dipping “contourite terraces” similar to those identified elsewhere in other contourite systems (Viana, 2001; Viana et al., 2002; Hernández-Molina et al., 2009, 2011b; Preu et al., 2013).

5.2. Contourite facies on the Storfjorden Trough Mouth Fan

The uppermost sedimentary facies on the mid continental slope of the Storfjorden Trough Mouth Fan are interpreted as contourites (Lucchi et al., in press). The composition of the sediments with mixed hemipelagic–glaciomarine components, lacking of shallow water bioclasts indicates deposition under hemipelagic conditions with lateral sediment advection as suggested by the high smectite content in the clay mineral assemblage. According to Junttila et al. (2010), the smectite is deriving from the hydrothermal alteration of the basalts of the Greenland-Faroe Ridge, Iceland and Vøring Plateau and transported into this area by the North Atlantic Current. Increasing smectite content is used as proxy for intensification of North Atlantic water mass input. Crude bedding and rough unimodal grain size spectra testify shear motion at the bottom by tractive currents, while polymodal grain size spectra, intense bioturbation and low C_{org} suggest strong benthic bioactivity associated with well oxygenated and nutrient-rich conditions compatible with contour currents (Stow and Holbrook, 1984; Chough and Hesse, 1985). Lucchi et al., (in press) compared this facies to the intensively bioturbated muddy contourites described by Stow and Holbrook (1984) in the North Atlantic and Laberg and Vorren (2004) in the Lofoten contourite drift. Similarly to the latter, the contouritic sediments on the Storfjorden mid slope may originate from along-slope sediment transport and deposition from intermediate water masses.

The lack of a geophysical evidence of contouritic deposits in the ancient record of the Storfjorden continental slope (where no sediment mounds can be identified) was related to episodic removal of contouritic deposits by glacigenic debris flows erosion during glacial maxima (Lucchi et al., in press).

5.3. Depositional mechanism

The depositional mechanism that we infer for the Isfjorden and Bellsund drifts is that of plastered drifts. The slope west of

Spitsbergen is swept by the West Spitsbergen Current (WSC), which is a persistent along-slope flow of Atlantic-derived water (e.g. Jonsson et al., 1992; Beszczynska-Möller et al., 2012). It is divided in two branches: the main WSC core, and its offshore branch, characterized by Norwegian Sea Deep Water. The main core, shallower than about 1000 m depth, shows velocities well above 10 cm/s and precisely above 20 cm/s in the decade-long time series of moorings across the Fram Strait (Fig. 4; Beszczynska-Möller et al., 2012). These velocities result in non deposition to the east of the contourite drifts and/or erosion in the uppermost part of the continental slope (Fig. 11). Conversely, the offshore branch of WSC, focused below about 1400 m depth, shows velocities of 9 cm/s and slower (Fig. 4; Beszczynska-Möller et al., 2012). These velocities (and the presence of suspended sediment, see below) result in deposition directly below the current pathway of the Norwegian Sea Deep Water within the offshore branch of WSC (Fig. 11).

The presence of suspended sediment is an essential condition for active deposition from bottom currents in oceans. Bottom currents may carry in suspension a considerable amount of fine material and particulate organic matter (McCave, 1985; Thomsen et al., 2002), which form the so-called nepheloid layer (Ewing and Thorndike, 1965).

According to Stow et al. (2008), sediment supply to the nepheloid layer can occur through a large variety of sedimentary and biological processes. For the contourite drifts west of Spitsbergen we infer that sediment supply occurred through: gravity mass processes during glacials; sediment laden turbid meltwaters during the initial phase of ice-sheet melting and retreat; and by a combination of hemipelagic settling and turbid high-density shelf-waters cascading down the slope during full interglacial conditions (*TS-turbidites* of Fohrmann et al., 1998). This is similar to what inferred for the Lofoten Drift in the Norwegian Sea, which probably originates from the deposition of suspended particles derived from winnowing of the shelf and upper slope (Laberg et al., 1999, 2002). Significant amounts of re-suspended material is known to be exported from the Barents Sea via cascading winter outflows of dense bottom water (Blindheim, 1989; Blaume, 1992). An example of sediment transfer that contributed to the sediment suspended into the Bottom Nepheloid Layer along the Barents Sea continental margin is reported by Thomsen et al. (2001).

In other glaciated margins there are various examples of transfer of sediments from the continental shelf to bottom currents that control the deposition of contourite drifts. In the NW Weddell Sea (Antarctica) contourite drifts develop on the continental slope in an area where Antarctic Bottom Water is formed through brine rejection in the polynyas (Smith et al., 2010). On the Antarctic Peninsula Pacific margin there is evidence that fast-flowing ice streams extended to the shelf edge under full-glacial conditions, which transferred sediments down the slope through small debris flows, slumps and turbidity currents that form channels on the continental rise (Dowdeswell et al., 2004). Large sediment drifts on the continental rise are thought to be produced from the fine-grained component of such turbidity currents, which is transported in a nepheloid layer within predominantly southwest-flowing bottom currents (Rebesco et al., 2002; Lucchi et al., 2002). In the deep (over 800 m) George V basin on the Antarctic continental shelf, the Mertz sediment drift was deposited under an energetic bottom current regime inferred to be related to the activation of a brine-rejection mechanism. This is linked to the formation of high-salinity shelf water in a coastal polynya, which causes winnowing of the shelf deposits (Presti et al., 2003).

In non glaciated margins, dense water cascading is inferred to be at the origin of contourites (and cascadites, which are considered very similar to shallow water contourites) and sediment drifts and bedforms deposited from contour currents (Gaudin et al., 2006; Verdicchio and Trincardi, 2006, 2008).

5.4. Age and location of the contourite drifts

Contourite drifts from the eastern Norwegian–Greenland Sea continental margin are reported only from Northern Norway (Nyk, Lofoten and Vesterålen drifts, Laberg et al., 1999, 2002) and Fram Strait (Vestnesa Ridge, Knipovich Ridge and the Yermak Plateau, Eiken and Hinz, 1993; Howe et al., 2008; Hustoft et al., 2009; Petersen et al., 2010; Geissler et al., 2011). The drifts we detected west of Spitsbergen lie just southeast of those identified by Eiken and Hinz (1993) and were not identified before. A Late Miocene age was inferred either for the Lofoten drift to the south (Laberg et al., 1999, on the base of regional seimostratigraphic correlation) and for the Vestnesa Ridge to the north (Eiken and Hinz, 1993 on the base of correlation to DSDP site 344 and inferred basement age). The onset of those drifts was ascribed to increased palaeo-circulation probably controlled by subsidence of the Greenland–Scotland Ridge (Laberg et al., 1999) and/or by late Cainozoic climatic cooling (Eiken and Hinz, 1993).

The onset of the drift growth west of Spitsbergen is identified by the development of the mounded, sigmoidal geometry above the underlying downslope thinning seismostratigraphic sequences and by the change in seismic facies (more laterally continuous and with relatively uniform amplitude within the drifts). For either the Isfjorden and the Bellsund drifts, the onset is identified in correspondence of reflector R4A (Figs. 7 and 8). The age of this reflector is inferred to be about 1.3 Ma. However, the age model is mostly based on interpolation using a linear sedimentation rate and a few dated levels in the older part of the glacigenic succession. Reflector R4A in the nearby site 986 corresponds to a distinct change in seismic character on the shipboard seismic record and a major change in depositional style (Shipboard Scientific Party, 1996). Below R4A there is a series of very strong reflectors corresponding to larger debris flows suggesting a dominance of mass-wasting activity. Above R4A, there are mostly low-amplitude reflectors inferred to correspond to more frequent small-scale mass-wasting events, probably related to changes in the style and frequency of glaciations (Shipboard Scientific Party, 1996) rather than to an increased palaeo-circulation. Thus the growth of the drifts studied by us is probably not related to the opening of the Fram Strait but more likely to the glacial history of the area. The onset of Isfjorden and the Bellsund drifts may originate from more favourable depositional conditions resulting from frequent episodes of small-scale mass-wasting events. Such events may have significantly contributed to transfer of suspended sediments into the Bottom Nepheloid Layer, similarly to the turbid plume episode analysed by Thomsen et al. (2001). The onset of these conditions may coincide with the Early Pleistocene glacial expansion and Trough Mouth Fan development produced by fast flowing ice streams supplying sediments to the shelf edge (Forsberg et al., 1999; Butt et al., 2000). A recent analysis of the seismostratigraphy of the Trough Mouth Fans on the North-Western Barents Sea margin (Rebesco et al., in press) suggests that the onset of such fans coincide with the R4A reflector, and hence precisely with the onset of the drifts. Such Early Pleistocene events in the Barents Sea are inferred to coincide with glacial expansions in the circum-Atlantic region (Knies et al., 2009). Caused by a cooling climate (Mudelsee and Raymo, 2005), in this time there were the first documented shelf edge glaciations with subglacial erosion most pronounced at the base of the ice streams (Andreassen et al., 2007). The Barents Sea during this period was characterized by a spatial and temporal interplay of sediment input from the ice sheet and episodes of sediment reworking on the continental slope (Laberg et al., 2010). We hence infer that the growth of the drifts west of Spitsbergen above the reflector R4A is related to the Early Pleistocene glacial expansion recorded in the area. As already noted by Laberg et al. (1999), high downslope input of glacigenic sediments during the late Cainozoic dominated over the relatively thin, interbedded contourite deposits locally identified on the eastern Norwegian–Greenland Sea continental margin (e.g. Yoon and Chough, 1993). Lucchi et al., (in press) ascribe the lack of contourite drifts on the Storfjorden Fan to consecutive erosion by glacigenic debris flows. The abrupt downslope termination of the contouritic deposits against the glacigenic debris flows visible in our seismic reflection data (Fig. 8) suggests that the latter are by far dominating. The disrupting dominace of glacigenic debris flows is evidenced also by the sub-bottom profiles (Fig. 9 B and C) that show erosion and modification of the contouritic deposits (when these are not acoustically masked by the energy-adsorbing debris flow lenses). Drift location is hence influenced by the downslope processes. This was already shown for the case of the infill drift, where contourites fill the depression generated by paleo land slide scars (Laberg et al., 2005). On the Vestnesa Ridge, contourites are inferred by Sarkar et al. (2011) to develop on the deeper slope while glacial progradation takes place on the upper slope. As the outbuilding of the shelf due to glacial progradation ceases due to lateral switching of the palaeo-ice stream, the contouritic deposits prograde upslope. We observe that the drifts west of Spitsbergen develop north (downcurrent) of a major trough (the Storfjorden Trough) in similar way with the Lofoten Drift, which is north (downcurrent) of the Trænadjupet Trough (Laberg et al., 1999), pointing to Storfjorden as the main source area.

The trend of the continental margin west of Spitsbergen is articulated in various parts due to the presence of outward-bulging glacigenic trough-mouth fans. These may have a role in controlling the position of the drifts. We observe that the development of the drifts west of the Spitsbergen is nurtured off the minor glacigenic Trough Mouth Fans (Isfjorden and Bellsund) but is hindered on the much larger Storfjorden Trough Mouth Fan. The location of the Isfjorden and the Bellsund drifts is probably due to relatively favourable depositional conditions in areas protected from large and frequent debris flows. And in fact they are located in inter-fan areas: the former between the Isfjorden and Bellsund fans and the latter between Bellsund and Storfjorden fans. In the case of these drifts, the protection from debris flows seems to us more important than other factors.

For the reasons above the Isfjorden and Bellsund drifts are inferred to contain the record of the regional palaeoceanography and glacial history since the Early Pleistocene. According to their seismic facies this record is supposed to be relatively continuous and expanded. It is hence suggested that these drifts may constitute and excellent target of future scientific drilling for palaeoclimatic reconstructions.

6. Conclusions

Two sediment mounds on the continental slope between 1200 and 1800 m depth west of Spitsbergen are described on the basis of multichannel seismic, sub-bottom, bathymetric and lithologic data. On the basis of their mounded morphology, the along-slope elongation and their internal sigmoidal geometry they are interpreted as contourite drifts. The upper continental slope, swept by the robust and persistent flow of West Spitsbergen Current (averaged velocities of more than 20 cm/s), is characterized by reduced- or by non-deposition (by-pass). The dense (cold and relatively saline) Norwegian Sea Deep Water forms a local maximum of the northward bottom flow at the depth of the contourite drifts. Occasionally, plumes of even higher density are also observed on the slope, spilling from the shallow Barents Sea where they are formed by cooling and sea ice formation. We consider it likely that the contourite drifts west of Spitsbergen are fed by such dense plumes of brine-enriched shelf water spilling from the Barents Sea since they show the largest bottom velocities and are energetic enough to supply suspended material (Fig. 6) to that depth in Fram Strait. The mechanism that we believe as responsible for the accumulation of contourites is hence sediment delivery by Norwegian Sea Deep Water episodically fed by dense shelf water plumes (Fig. 11). The onset of the contourite drifts is inferred to coincide with the Early Pleistocene glacial expansion and Trough Mouth Fan development on this margin, which resulted in enhanced supply of sediments to and beyond the shelf edge. The development of contourite drifts in this region indicate that a similar bottom-intensified current has been prevailing at least since the Early Pleistocene, and that the climatological forcing (i.e. supply of dense deep waters in the Norwegian Sea and/or cooling over the Barents Shelf) has prevailed for this time.

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