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Abstract: We present new evidence for a grounded ice sheet and subsequent erosion by large fields of coherent icebergs for the central and northern Yermak Plateau (80.6°N to 82.2°N). Sediment echosounder and swath bathymetry data were combined with seismic reflection profiles and reveal at least three different glacial events marked by erosional unconformities: (i) An erosional unconformity was observed at ~70 to 90 m below seafloor down to depths of more than 850 m present water depth, extending to ~82°N. The erosional unconformity is overlain by an acoustically chaotic layer of ~50 m thickness interpreted as a diamicton originating from a grounded ice sheet. The erosional unconformity and the overlying diamicton can be correlated to the overconsolidated sediments found at ODP Site 910 at a sediment depth between ~19 and 70 to 95 m. The oldest sediments just above the overconsolidated sediments are of late Early Pleistocene age (MIS19/20) and provide a minimum age for the grounding event. (ii) Parallel to sub-parallel mega-scale lineations are observed on large parts of the plateau west and northeast of the Sverdrup Bank at water depths between 725 and 850 m. These lineations are mainly oriented NNE-SSW and were quite likely formed by the keels of deep-draft, megascale tabular icebergs entrapped in a coherent mass of icebergs and sea ice. The lineations are of late Middle Pleistocene age. (iii) Smaller-scale curvilinear plow marks were found in the southernmost part of our study area at water depths between 640 and 775 m. These were possibly caused by single icebergs and are of Late Pleistocene age. Iceberg scours are also found on three basement heights on the Yermak Plateau. These, however, cannot be assigned to specific events; they might as well originate from additional glacial phases.
The western (at >850 m water depth) and eastern (at >1000 to 1200 m water depth) flanks of the Yermak Plateau are relatively featureless, and indicate the maximum depth of a grounded ice sheet and of iceberg armadas probably entrapped in sea ice.

***Highlights**

Highlights:

- New evidence for ice sheet grounding on the northern Yermak Plateau
- Ice sheet grounding dates to late Early Pleistocene
- Overlain by plow marks of probably MIS6 age
- Plow marks mostly oriented in NNE-SSW direction
- Plow marks likely originate from coherent mass of icebergs from NNE towards SSW

Ice sheet grounding and iceberg plow marks on the northern and central Yermak Plateau revealed by geophysical data

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Abstract

We present new evidence for a grounded ice sheet and subsequent erosion by large fields of coherent icebergs for the central and northern Yermak Plateau (80.6°N to 82.2°N). Sediment echosounder and swath bathymetry data were combined with seismic reflection profiles and reveal at least three different glacial events marked by erosional unconformities: (i) An erosional unconformity was observed at ~70 to 90 m below seafloor down to depths of more than 850 m present water depth, extending to ~82°N. The erosional unconformity is overlain by an acoustically chaotic layer of ~50 m thickness interpreted as a diamicton originating from a grounded ice sheet. The erosional unconformity and the overlying diamicton can be correlated to the overconsolidated sediments found at ODP Site 910 at a sediment depth between ~19 and 70 to 95 m. The oldest sediments just above the overconsolidated sediments are of late Early Pleistocene age (MIS19/20) and provide a minimum age for the grounding event. (ii) Parallel to sub-parallel mega-scale lineations are observed on large parts of the plateau west and northeast of the Sverdrup Bank at water depths between 725 and 850 m. These lineations are mainly oriented NNE-SSW and were quite likely formed by the keels of deep-draft, megascale tabular icebergs entrapped in a coherent mass of icebergs and sea ice. The lineations are of late Middle Pleistocene age. (iii) Smaller-scale curvilinear plow marks were found in the southernmost part of our study area at water depths between 640 and 775 m. These were possibly caused by single icebergs and are of Late Pleistocene age. Iceberg scours are also found on three basement heights on the Yermak Plateau. These, however, cannot be assigned to specific events; they might as well originate from additional glacial phases.

The western (at >850 m water depth) and eastern (at >1000 to 1200 m water depth) flanks of the Yermak Plateau are relatively featureless, and indicate the maximum depth of a grounded ice sheet and of iceberg armadas probably entrapped in sea ice.

1 Introduction

The Arctic Ocean cryosphere is presently characterized by a strongly dynamic sea ice cover that varies temporally and spatially in extent, thickness and density (e.g., Laxon et al., 2003; Parkinson et al., 1999; Woodgate et al., 2010). Ice shelves and tidewater glaciers play only a minor role and are restricted to few locations in the Canadian Arctic, Greenland and Siberia (Dowdeswell, in press; Jeffries, in press; Reeh, in press; Stein and Macdonald, 2004). Meanwhile, there are some ideas about the history of the sea ice cover (Polyak et al., 2010, and references therein), whereas the existence and extent of marine-based ice sheets and ice shelves in the Cenozoic is still an open issue. Almost half a century ago, Mercer (1970) postulated that a complex ice cover consisting of ice shelves and ice grounded far below sea level could have existed in the Arctic Ocean prior to the last glaciation. The idea of Mercer (1970) has been further developed by Hughes and Grosswald (Grosswald, 1988; Grosswald and Hughes, 1999; Grosswald and Hughes, 2002; Hughes et al., 1977) who arrived at a model that involved a large circum-Arctic ice shelf during the Pleistocene glacial maxima. They suppose that at least the western Arctic Ocean was covered by a thick pan-Arctic floating ice shelf that was thickest over the lowlands of Wrangel Island and extended far into the Arctic Ocean, reaching even the Lomonossov Ridge. The ice sheet reconstructions by the ESF QUEEN (Quaternary Environment of the Eurasian North) Project (Svendsen et al., 2004) rejected this hypothesis for the Eurasian Arctic, concluding that the major glaciations since MIS 6 did not extend across the Eurasian shelf edges except for an advance across the Yermak Plateau in MIS 6. Nevertheless, it was further stated by the QUEEN project that during the Late Saalian, an ice complex formed over Eurasia, which was probably one of the most extensive Quaternary ice complexes in this part of the world. In addition, Ottesen and Dowdeswell (2009) showed that ice in northwesternmost Spitsbergen did not extend onto the Yermak Plateau during the Late Weichselian.

The QUEEN reconstructions, however, were based on few marine geological and geophysical data from the Central Arctic Ocean. Since the 1990s, the spatial coverage with bathymetric and echosounder/seismic profiles is becoming continuously denser (e. g., Engels et al., 2008; Jakobsson, 1999; Jakobsson et al., 2008b; Kristoffersen et al., 2004; Polyak et al., 2007; Polyak et al., 2001; Vogt et al., 1994). Based on these data and a compilation of new data from different areas such as the Chukchi Borderland, the southern Yermak Plateau, Morris Jesup Rise and the southern Lomonosov Ridge north of Greenland, Jakobsson et al. (2010) proposed the existence of a large marine-based ice sheet with an ice shelf of MIS6 age in the Amerasian Arctic Ocean.

Glacial features such as mega-scale lineations and iceberg plow marks form the main evidence for extensive glacial activity in the marine realm, and they are now reported from areas as far offshore as the central Lomonosov Ridge at water depths of up to >1000 m (Jakobsson, 1999; Jakobsson et al., 2008b; Kristoffersen et al., 2007; Kristoffersen et al., 2004; Polyak et al., 2001) as well as from more proximal areas such as the Chukchi Sea (Polyak et al., 2007), Northwind Ridge (Jakobsson et al., 2005; Jakobsson et al., 2008b), Beaufort Sea (Engels et al., 2008), Barents Sea (Bellec et al., 2008) or offshore Greenland and Svalbard (Dowdeswell et al., 2010a; Dowdeswell et al., 2010b; Evans et al., 2002; Kristoffersen et al., 2004; Kuijpers et al., 2007; Ottesen et al., 2007; Vogt et al., 1994; Winkelmann et al., 2010). Systematic investigations of submarine highs in the deep Arctic Ocean are still rare due to the heavy pack ice cover but, due to the seasonal decrease in ice cover in the past few years, the marginal Arctic Ocean is becoming increasingly accessible. The Yermak Plateau is the largest submarine high at the northern Barents Sea continental margin that is shallower than 1000 m water depth. The southern part of the Yermak Plateau has mainly been studied (Bergmann, 1996; Dowdeswell et al., 2010b; Jakobsson et al., 2010; Kristoffersen et al., 2004; Vogt et al., 1994). To our knowledge, Vogt et al. (1994) were the first to map the seafloor landforms of the southern Yermak Plateau, northwest of Spitsbergen. Linear and curvilinear sea-floor features interpreted as iceberg plow marks were found at various water depths ranging from 450 to 850 m. They discovered that the southernmost plateau crest, with modern water depths of 510 to 530 m, is nearly bare of any plow marks (except for some single, fresh ones with variable but predominantly NE trends) and ascribe this fact to a grounded ice sheet beveling all earlier surface characteristics. Similar features were observed by Bergmann (1996) close to ODP Site 910 (80°16'N, 6°35'E; 556 m water depth; Myhre et al., 1995) on a single sediment echosounder profile, but were interpreted as related to bottom currents. Kristoffersen et al. (2004) identified an erosional unconformity on seismic profiles that cross ODP Sites 910 to 912. They showed that the erosional unconformity is limited by water depth (~830 m) and only occurs at the shallow Site 910. At Site 910, overconsolidated sediments were identified between ~19 and 70 to 95 m below seafloor, and biostratigraphy suggests a hiatus in the lower part of the overconsolidated section. Kristoffersen et al. (2004) proposed that deep draft icebergs exiting the polar basin removed this part of the stratigraphy. Dowdeswell et al. (2010b) recently published data from the southern to central Yermak Plateau that are now perfectly complemented towards north by our study. They identify both mega-scale lineations and curvilinear smaller lineations on the southern part of the Yermak Plateau. They relate the curvilinear, smaller lineations to single icebergs (some probably with several keels), while the mega-scale lineations in their opinion can be either caused by grounded ice from SSE or a floating ice-shelf remnant or mega icebergs from NNW.

In the past years, systematic geophysical and geological surveys have extended the database further to the north (Geissler and Jokat, 2004; Jokat, 2003; Jokat et al., 2008; Ritzmann and Jokat, 2003; Geissler et al., unpubl. data) that perfectly complement the previous investigations. Therefore, our study gives a systematic overview of the different seafloor features that are observed on the central and northern Yermak Plateau, and interprets them in terms of their glacigenic origin. Additionally, we attempt to put these features into a temporal framework based on ODP Leg 151 Site 910 that was drilled on the crest of the southern Yermak Plateau in 1993 (Myhre et al., 1995) and gives a further insight into the earlier glacial history of this area.

2 Study area

The bow-shaped Yermak Plateau is situated in the northeastern part of the Barents Shelf (Fig. 1). It forms the northernmost plateau of the Eurasian plate and is bounded by the Fram Strait to the west, the deep Nansen Basin to the north and east and the Svalbard archipelago to the south. The Yermak Plateau has water depths in the range of ~700 to 800 m over large parts, but is as shallow as 400 m at its central part where basement heights are found. Sediments of up to 1000 m thickness filled the initially rough basement morphology of the Yermak Plateau (Ritzmann and Jokat, 2003; Geissler et al., unpubl. data). The Fram Strait west of the Yermak Plateau is the only deep-water connection between the subpolar seas and the Arctic Ocean. The Yermak Plateau is located in the surface water inflow path of the relatively warm Atlantic Water into the Arctic Ocean. At roughly 80° N, i.e. south of the Yermak Plateau, the inflowing Western Spitsbergen Current splits up into three branches: the western branch turns immediately south (counterclockwise) and forms the Return Atlantic Current; the eastern branch flows eastwards along the continental slope of the Svalbard Archipelago as Spitsbergen Branch, and the Yermak branch flows north and then east around the northwestern corner of the Yermak Plateau (Manley et al., 1992) (Fig. 1).

3 Data acquisition

All hydroacoustic and seismic data used in this study were acquired in parallel during expeditions on *RV Polarstern*. Data from the central part of the Yermak Plateau were mainly acquired during the ARK-XVIII/2 expedition in 2002 (Jokat, 2003). In 2004, excellent ice conditions allowed us to extend the seismic and hydroacoustic survey to the northern part of the Yermak Plateau during the ARK-XX/3 expedition (Stein, 2005). Navigation and positioning of all profiles used GPS in connection with the ship's integrated inertial navigation system (MINS). All sediment echosounder data used in this study were acquired using the hull-mounted PARASOUND system (Atlas Hydrographic, Bremen, Germany) installed on *RV Polarstern*. Water depths were taken from the PARASOUND system applying a mean water sound velocity of 1500 m/s. Mainly good weather, calm seas and a ship speed of around 5 knots provided excellent measuring conditions during both cruises. Only in the most northerly areas, the data acquisition during ARK-XX/3 was strongly affected by moderate to heavy sea ice conditions causing noisy records with some traces missing. Bathymetric surveys were performed using *RV Polarstern's* deep-water multibeam system DS-2 (Atlas Hydrographic) that operates on a frequency of 15.5 kHz. A transmission beam aperture of 90° was used during both expeditions, resulting in a swath width of twice the mean water depth. Each ping of the Hydrosweep DS-2 system provides 59 depth values (Pre-Formed Beams) perpendicular to the ship's longitudinal axis (Gutberlet and Schenke, 1989). Bathymetric data cleaning and post-processing was thoroughly done comprising outlier rejection and editing of the navigation data using CARIS-HIPS (Jokat, 2003; Stein, 2005). The dataset was gridded with 20 m spacing using GMT software (Wessel and Smith, 1991).

Seismic reflection data were used for comparison with the sediment echosounder and the bathymetric data in order to distinguish between sediment surface structures that can be related, for example, to bottom currents and glacigenic processes, and structures that exist due to underlying morphological features such as structural heights of the basement. These new seismic data from *RV Polarstern* expeditions in 2002 and 2004 are of better quality than previously published data and allowed a more detailed study of already known erosional unconformities. Seismic data were processed using standard techniques (bandpass filtering, CMP sorting, NMO corrections, stacking, and f-k-filtering (Geissler et al., unpubl. data). Tracklines of all seismic, sediment echosounder and bathymetry profiles used in this study are shown in Fig. 2.

4 Classification of sub-marine landforms on the Yermak Plateau

For mapping of the different acoustic facies types (Fig. 3), printouts and digital images of the ARK-XVIII/2 and ARK-XX/3 sediment echosounder data were visually classified in combination with the associated bathymetric images according to the internal structure visible in the sediment echosounder data (Fig. 4) as well as their surface roughness and features (Fig. 5). Seismic profiles were additionally used to map features deeper than the penetration of the sediment echosounder (Figs. 6 and 7). A classification into eight acoustic facies types was chosen for this study. These eight facies types can be combined into three main groups that characterize the seafloor of the Yermak Plateau: (i) the facies type along the eastern and western flank of the Yermak Plateau at depths not influenced by glacigenic features (facies type 1); (ii) facies types influenced by glacigenic features (facies types 2 to 5), and (iii) the basement heights (facies type 6) and the facies types associated with these elevated zones (facies types 7 and 8).

4.1 Eastern and western flank of the Yermak Plateau

Sediments mapped as facies type 1 (Figs. 4a, b and 5a) cover both the eastern and the western flank of the Yermak Plateau (Fig. 3). They are characterized by well-layered, parallel sediments at greater water depths (western flank: mainly below 850 m water depth; eastern flank: mainly below 1000 to 1200 m water depth). Penetration depth of the echosounder system varied between 25 and >50 m, the latter indicating the presence of soft, unconsolidated muds. At the eastern part of the Yermak Plateau flank and around the Mosby Seamount in the Sophia Basin, associated with a large slope failure event (Hinlopen/Yermak megaslide; Vanneste et al., 2006; Winkelmann et al., 2008; Winkelmann et al., 2006; Winkelmann and Stein, 2007), staircase-like structures *sensu* Winkelmann et al. (2008) can be observed mainly in the lower part of the flank (Fig. 4b). Both the sediments on the eastern and the western Yermak Plateau flank are partly intercalated by large mass movement deposits of up to >10 m thickness.

4.2 Glacigenic features on the Yermak Plateau

At least three different generations of glacigenic features marked by erosional unconformities left a clear imprint on the Yermak Plateau:

(i) large-scale lineations, i.e. crests and associated troughs that are oriented parallel to the trough axis, with a crest-to-trough depth of up to 25 m, and a crest-to-crest wavelength of several hundred meters to > 1 km. These lineations at first glance resemble those found by other authors in the Arctic as well as in the Antarctic realm (e.g. Anderson et al., 2001; Canals et al., 2000; Clark, 1993; Dowdeswell et al., 2010a; Dowdeswell et al., 2004; Wellner et al., 2001). However, this type of lineations was originally found in bathymetric cross-shelf troughs associated with ice stream flow (e.g., Ottesen et al., 2005). The lineations on the Yermak Plateau are obviously not associated with ice streams, but were caused by either the keels of an ice sheet bulldozing over the plateau or by a series of deep-draft mega-scale tabular icebergs caught in a coherent field of icebergs mixed with multiyear sea ice. All glacigenic features of this type are draped, but not leveled, by well-stratified hemipelagic sediments of ~5 to >20 m thickness, leaving, thus, a clear signal in the bathymetric data. They are oriented parallel to sub-parallel in NNE-SSW direction with a few exceptions in NNW-SSE direction. The length of these mega-scale lineations cannot be estimated as they extend well beyond the small stripes of ocean floor that were scanned by the bathymetry swath during our seismic surveys. These mega-scale lineations are found in facies types 2 to 4 (Figs. 4c to 4e, 5b, 5d and 5g).

(ii) In the more southern part of the Yermak Plateau, and scattered on the basement heights described below, randomly distributed and often curvilinear lineations were observed (Dowdeswell et al., 2010b; Vogt et al., 1994) and interpreted as keel marks of single icebergs in analogy to other studies (Dowdeswell and Bamber, 2007; Dowdeswell et al., 1993). These plow marks are draped with up to 5 m of sediments and seem to be younger than the mega-scale lineations. These curvilinear plow marks were mapped as facies type 5 (Figs. 4f and 5c).

(iii) In almost all seismic sections, an erosional unconformity is visible at roughly 70 to 90 m depth below seafloor (Figs. 6 and 7). This is well beyond the penetration of the sediment echosounder, therefore this unconformity was not observed in these data. The erosional unconformity indicates that large parts of the older, well-stratified sediments that initially built up the Yermak Plateau were eroded (Figs. 6 and 7). The unconformity is overlain by an acoustically massive sediment layer of ~50 to 60 m thickness. The upper boundary of the acoustically massive sediment layer is perfectly visible in the sediment echosounder data (Fig. 4c to e) and shows a rather hummocky surface. This disconformity, in turn, is covered by well-stratified sediments of varying thickness (5 to 25 m) with incisions (facies types 2 to 5).

Facies type 2 (Figs. 4c and 5b) (760 to 825 m) is characterized by mega-scale lineations cut into the underlaying acoustically massive unit, with a drape of up to 25 m of well-stratified sediments, and a rather smooth surface. The mega-scale lineations are parallel to sub-parallel and mostly oriented in NNE-SSW direction with a crest-to-trough height of mainly ~5 m up to 10 m at most. Widths calculated from echosounder data are in the range of 1 to several km, but given that these features are lacking in sharp edges on both swath and acoustic data, this could be overestimating the real, initial widths (Fig. 4c). Facies type 2 is found only in the northeastern part of the Yermak Plateau, i.e. northeast of the elongated Sverdrup Bank and embracing the northernmost small basement height (Fig.3).

Facies type 3 (Figs. 4d and 5d) is similarly characterized by parallel to sub-parallel NNE-SSW mega-scale lineations, but covered by only ~10 to 15 m well-stratified sediment. Mega-scale lineations have a crest-to-trough depth of up to 30 m, but are mostly in the range of ~10 m. Packages of several plow marks always have the same orientation, but neighboring packages often are slightly different by only a few degrees. Facies type 3 is found in water depths of approximately 725 to 850 m, and is located on the northwestern part of the Yermak Plateau (Fig. 3). The transition to facies type 2 is smooth. Both the lineations of facies types 2 and 3 have the same orientation, but the seafloor is generally much smoother in facies type 2, and shows considerably more distinct mega-scale lineations in facies type 3. The transition between facies types 3 and 7 (described below) is also smooth and seems to be mostly dependant on water depth (approximately 775 to 800 m).

Facies type 4 (Fig 4e) is characterized by some single mega-scale lineations (some larger ones are up to 20 m deep from crest to trough, but most of them are only around ~5 m deep with a width of several hundred to >1 km) covered by ~5 to 10 m sediment on top of the acoustically chaotic facies; the sedimentary cover is slightly thicker closer towards the Yermak Plateau flank. The single lineations can clearly be identified in the subbottom profiles (Fig. 4e), but are slightly less distinct in the bathymetry data (Fig. 5g) with their edges being smoother than in facies type 3. Orientation is mostly NNE-SSW with a few exceptions in NNW-SSE direction. Facies type 4 is located south of facies type 3 at similar water depths between 740 and 825 m (Fig. 3).

In facies type 5 (Fig. 4f), the lineations have little sediment cover (~5 m) and, thus, seem to be rather young. They are oriented irregularly (with a subjective accumulation of directions oriented between NNE-SSW and NNW-SSE), some of them curvilinear. They also show rather variable shapes: some are as deep as >30 m from crest to trough, most however are more in the range of 5 m depth with a width of up to several hundred meters. Only between 81° to 81.16°N and 5° to 6°E, a rather undisturbed patch of several parallel lineations resembling the mega-scale lineations discussed above clearly trending NNW-SSE is observed. Crosscutting between the different lineations is common, but seems to be random. All lineations are incised into layered sediments that exhibit an earlier erosional subsurface. Facies type 5 is located south of the western basement height at 640 to 775 m water depth, between facies types 7 and 4 (Fig. 3). The transition from facies type 7 to type 5 is smooth, and the transition between facies types 4 and 5 does not show crossing lineations in our data and thus does not allow a relative age estimate; nevertheless, we think that the curvilinear lineations are younger due to their thinner sediment cover.

4.3 Basement heights and associated zones

An outstanding feature on top of the plateau is the Sverdrup Bank (Eiken, 1993, 1994). It stretches approximately in N-S direction (Fig. 2). The Sverdrup Bank is a massive block with steep flanks to the west and east. In its northern, narrower part, the bank forms a bathymetrical high and has an eroded top. Towards the south, the Sverdrup Bank broadens, deepens, and becomes partly covered by Late Cenozoic sediments. Southwest of the Sverdrup Bank at approximately 81.38°N, 5.55°E, another small, flat-topped bathymetric height exists, and a third basement height with rough topography is found northeast of the Sverdrup Bank at approximately 81.94°N, 8.6°E (Fig. 2).

The three basement heights were mapped as facies type 6 (Figs. 3, 4g and 5f). (a) In the northernmost part at ~81.8°N (750 to 775 m water depth), the Sverdrup Bank is furrowed with steep incisions as deep as 20 m and has almost no sediment cover. Further south at ~81.6°N, the Sverdrup Bank is shallower (500 to 525 mbsf), covered by roughly 5 m of sediment and has wide, deep incisions (up to 25 m deep) superimposed by small-scale incisions (<5 m deep). In its central part at ~81.4°, the Sverdrup Bank is even shallower (440 to 450 m water depth) with small-scale incisions (<5 m) with up to 5 m sediment cover. Towards the south

(81.2°), the Sverdrup Bank is slightly asymmetric with ~550 m water depth in the western and ~625 m water depth in the eastern part. Its surface is less furrowed than further north, furrows are rather small and the sediment cover is around 5 m. All furrows in this part and towards the northern tip of the Sverdrup Bank are oriented randomly. In the southernmost part of the Sverdrup Bank (81.1°N), the basement rather forms a depression than a height (1025 to 1150 m water depth) relative to its surroundings; seismic data however confirm that this area is still part of the Sverdrup Bank (Geissler et al., unpubl. data). Its surface also differs remarkably with deep, smooth, asymmetric furrows (up to >30 m deep) in a definitely hard stratum, and mainly inside the furrows 5 to 10 m sediment have accumulated. Seismic data clearly show old, pre-glacial sediments with asymmetric normal faults (Geissler et al., unpubl. data). (b) The western basement height is rather small. It is slightly asymmetric with water depths of approximately 715 m in the eastern and 690 m in the western part, both parts separated by a small depression. Some smaller mass movement deposits (5 to 10 m thick at most) have accumulated in this local depression, while both local heights are neither furrowed nor covered by sediments. (c) The northeastern basement height resembles the western one in terms of size with a water depth of approximately 725 to 750 m. It has steep, furrowed flanks, and also its flat surface is furrowed with some irregular sediment cover of 5 m at most; furrows are oriented randomly with a few long, distinct ones oriented strictly NNE-SSW cutting through all others.

Facies type 7 (Figs. 4h and 4i) is located directly along the foot of the southwestern flank of the Sverdrup Bank and also almost embraces the western basement height (Fig. 3). It is characterized by well-layered, soft drift-type sediments (echosounder penetration sometimes up to ~50 m) most likely related to bottom current activity. A local elongated depression along the foot of the Sverdrup Bank in the eastern part of the drift deposits is quite likely caused by high-velocity bottom currents along the Sverdrup Bank leading to winnowing of fine-grained material and – if at all – only little sedimentation inside this channel structure and higher sedimentation rates with well-layered contourites further away (towards southwest) from the Sverdrup Bank. Given the fact that drift deposits are accumulated to the right of a bottom current on the Northern Hemisphere due to Coriolis deflection, this points at a NNW-SSE direction for the corresponding bottom current, which is in approximately opposite direction to the northeastern direction of the inflowing North Atlantic water masses at and near the ocean surface.

Seismic data reveal that the older erosional event affected the western part of the area where facies type 7 is observed, but never affected the areas close to the elongated Sverdrup Bank. The large sediment packages that are visible below this area are built up by a series of drift bodies/contourites that are related to (changing) bottom current patterns (Geissler et al., unpubl. data).

Large mass transport deposits are intercalated with the drift-type sediments of facies type 7 (Figs. 4h and 4i). They quite likely originate from the Sverdrup Bank and were caused e.g. by horizontal transport of sediments from north (or NNE) towards south (or SSW) and then further downslope. Mass transport deposits are found at different depths within the well-layered sediment package; this points at different ages and, thus, different events when material was transported across the Sverdrup Bank.

Facies type 8 is found in a small and limited area only, in close proximity to the eastern flank of the Sverdrup Bank (Fig. 3), and is characterized by contourite-type sediments of >25 m thickness, with some distinct channels (up to 25 m crust-to-trough height) probably related to modern bottom current activity. Sediment accumulation points at a S-N direction of the bottom currents on the eastern flank of the Sverdrup Bank. The sedimentary character of facies type 8 is largely comparable with facies type 7.

5 Stratigraphy, origin and (relative) age of the glacigenic features on the Yermak Plateau

5.1 Ice sheet grounding on the entire Yermak Plateau prior to the late Early Pleistocene

The erosional unconformity found below almost the entire area mapped in this study (except of areas very close to the Sverdrup Bank and at the Yermak Plateau flanks), at a depth of ~70 to 90 m below seafloor, points at an early glacial event with erosion of the older sediments of the Yermak Plateau and the shallow parts of the basement heights. The erosional unconformity is overlain by an acoustically transparent to chaotic layer (Figs. 6 and 7). We think that this erosional discordance was created by a major grounded ice sheet with its source at Svalbard and/or the Barents Sea with a likely extent to at least 82° N and down to depths of more than 850 m present water depth. Such a major grounded ice sheet would move large amounts of sediments towards north and quite likely also down-slope on the northern Yermak Plateau flanks. The data quality, however, is poor in the northernmost area due to heavy ice conditions during data acquisition. Debris flows at the foot of the northern flank can therefore not be identified in the sediment echosounder profiles. The pronounced, acoustically transparent to chaotic layer overlaying the erosional horizon is interpreted as a diamicton formed by this massive ice sheet. All later glacial features described in the previous sections (i.e. facies types 2 to 5) only disturbed the uppermost meters of this layer and are overlain by 5 to 25 m of well-layered sediments.

With the dense grid of seismic lines on the Yermak Plateau (Fig. 2), the erosional unconformity can be traced through crossing points from the northernmost profiles at about 82°N towards ODP Site 910, where a clearly overconsolidated sediment interval was identified between ~19 and 70 to 95 m below sea floor (Shipboard Scientific Party, 1995) (Fig. 7), characterized by a large increase in bulk density as well as in sediment shear strength (O'Regan et al., 2010). The base of this interval corresponds to the erosional unconformity, while the upper boundary of the diamicton found on the seismic profiles corresponds to the upper boundary of the overconsolidated sediment interval identified at ODP Site 910. The sediment interval was attributed to a grounded, marine-based ice sheet (Flower, 1997; O'Regan et al., 2010; Shipboard Scientific Party, 1995). The youngest sediments on top of the overconsolidated interval at ODP Site 910 were initially dated by Flower (1997) to MIS16/17 (676 kyr, Lisiecki and Raymo, 2005) by means of oxygen isotope stratigraphy. The presence of a hiatus in Hole 910A was discussed controversially during shipboard studies (Shipboard Scientific Party, 1995), but was later confirmed by Knies et al. (2007) based on new stable oxygen isotope data and a new magnetostratigraphy. The hiatus spans about 200,000 years in Hole 910A, and the youngest sediments above the unconformity have a slightly older age of MIS 19/20 (790 kyr) (Knies et al., 2007). The age of the sediments that directly overlay the diamicton gives a minimum age for the grounding event causing the erosional unconformity.

To our knowledge, Kristoffersen et al. (2004) were the first authors to point out this erosional unconformity in seismic data. They, however, suggested that the erosional unconformity was formed by iceberg armadas that passed the Yermak Plateau from northeast rather than by an ice sheet grounding as was interpreted from the ODP Site 910 data. They further suggested that the area west of the Sverdrup Bank is characterized by a depositional wedge, where sediments bulldozed by iceberg armadas were deposited. We could only identify this wedge on a single seismic profile that is located quite close to profile AWI-91128 presented by Kristoffersen et al. (2004), where the basement itself has a characteristic U-shape that allows the formation of such a wedge. This wedge, thus, seems to be a rather local phenomenon.

5.2 Glacial features of late Middle Pleistocene age

The mega-scale lineations visible in facies types 2 to 4 reach well beyond both sides of our swaths (Fig. 5). We, thus, cannot estimate their length. However, the same distinct pattern of patches of several lineations seems to be repeated over more than just one swath; mega-scale lineations, thus, can be up to several tens of kilometers long. The large set of these parallel to sub-parallel mega-scale lineations as seen on wide parts of the (central and northern) Yermak Plateau, in our understanding, points at either a detached piece of an ice sheet with several distinct keels leaving strong imprints on the ocean floor, or at a large field of coherent icebergs, quite likely trapped in multiyear ice and, thus, traveling strongly uniform with their keels leaving parallel mega-scale lineations on the ocean floor (the origin of such lineation is discussed e.g. in Dowdeswell et al., 2010b, and references therein). We, however, favor the latter, as patches of distinct lineations are sometimes slightly turned in orientation if compared to other patches. Rather than at remains of an ice sheet, this points at groups of icebergs trapped in multiyear ice, traveling highly uniform over long distances but not completely synchronously.

The mega-scale lineations that were mapped as facies type 2 are smooth and filled by significantly thicker packages of sediment than those of facies types 3 or 4. This thicker sediment cover might indicate an older age of these lineations, but may also simply originate from higher sedimentation rates east of the Sverdrup Bank due to bottom current activity. The currents along the western Sverdrup Bank flank are quite likely responsible for the different thickness of the sediments draping the mega-scale lineations of facies types 3 and 4, with enhanced winnowing closer to the flank resulting in generally thicker sediment layers towards the western flank of the Yermak Plateau. As discussed in the description of facies types 7 and 8, the bottom currents along the flanks of the Sverdrup Bank have opposite directions with a NNW-SSE trend on the western and a SSE-NNW trend on the eastern flank. The lineations of facies type 4 are generally smoother than those of adjacent facies type 3. Furthermore, they often do not occur in patches but as single, long lineations. The area where facies type 4 is mapped is in the prolongation of the Sverdrup Bank that definitely forms an obstacle for NNE-SSW trending icebergs with its shallow water depths; the rare occurrence of lineations “downstream” this area, thus, gives further evidence that the iceberg patches came from NNE and not vice versa.

Dowdeswell et al. (2010b) show streamlined subglacial landforms on the southern Yermak Plateau crest with an NNE-SSW orientation similar to the mega-scale lineations mapped in our facies types 3 to 4.

Using a set of different short cores as well as data from ODP Site 910, they suggest that these glacial lineations were quite likely formed during MIS6, similar to the estimate by Jakobsson et al. (2010) who use core 143SGC recovered during the *Ymer* 1980 expedition to date the oldest sediments filling these lineations. This core, however, has a total length of 3.45 m with a basal MIS5 age, while the erosional unconformity formed by these lineations is at approximately 7 m sediment depth at this place. The record at ODP Site 910 in close proximity (distance: 8.4 km) and comparable water depth (Site 910: 556 m, 143SGC: 560 m) to 143SGC reveals an MIS6.6 age at ~6 m sediment depth, while at ~7.5 m, an older age of MIS8.4 is given (Knies et al., 2009). MIS6 must thus be considered a first tentative age assignment for the respective erosional event, and this age remains to be fully confirmed from studies of new cores penetrating all the way through the sediment draping the mega-scale lineations on the Yermak Plateau.

Furthermore, mass transport deposits intercalated in the well-stratified layers of facies type 7 west of the Sverdrup Bank (Fig. 4h and 4i), are quite likely fed by sediment that was bulldozed from NNE over the Sverdrup Bank and downwards on its SSW flank. They occur at different stratigraphic levels and are thus of different ages. This points at more than just one single event with deep-draft, megascale tabular icebergs entrapped in a coherent mass drifting from the more central part of the Arctic Ocean towards the Fram Strait. Jakobsson et al. (2010) suggest a major glaciation of the Arctic realm during MIS6, with major ice sheets in Eurasia (Svalbard-Barents-Kara Sea) as well as on Greenland and Northern America. This is also one of the three scenarios discussed in Dowdeswell et al. (2010b). In their model, the Yermak Plateau is not covered by the MIS6 Eurasian ice sheet. This is consistent with our interpretation of deep-draft, mega-scale tabular icebergs entrapped in sea ice as an origin for the NNE-SSW trending mega-scale lineations rather than an ice sheet advance from south. Nevertheless, the mass transport deposits that occur in different stratigraphic levels clearly indicate that the Yermak Plateau was subject to massive iceberg scouring more than once.

5.3 Late Pleistocene glacial features

Facies type 5 with its randomly oriented, curvilinear lineations (Figs. 4f and 5c) at water depths of 640 to 775 m does obviously neither originate from a grounded ice sheet nor from movements of coherent icebergs. These features are quite likely plow marks of single, deep-keeled icebergs that might have been smaller than those responsible for the mega-scale lineations on the central Yermak Plateau. Bergmann (1996) found similar features close to ODP Site 910 on a single sediment echosounder profile, but supposed that these were related to bottom currents. Also Vogt et al. (1994) identified similar curvilinear features with little to no sediment cover on the southernmost tip of the Yermak Plateau, close to ODP Sites 910 to 912, and interpreted them as single iceberg plow marks.

Dowdeswell et al. (2010b) identified large- and small-scale, randomly oriented, curvilinear features just south of where we mapped facies type 5. These features seem to be of similar origin, even though the latter were found in greater water depths. Dowdeswell et al. (2010b) interpreted these features as plow marks from single icebergs or, if patches of such features are parallel over a certain distance, as plow marks left behind by multi-keeled large-scale icebergs. Fortunately, they were able to map small-scale lineations that crosscut the larger-scale ones that were supposed to be of MIS6 age, and – due to crosscutting relationships – could give a relatively younger age for the former. This suggests a younger age of facies type 5 relative to facies type 3 lineations, which is in good agreement with our interpretation of a thinner sediment cover suggesting a younger age.

5.4 Glacial features on the basement heights

The basement heights are the shallowest areas on the Yermak Plateau (with exception of the southernmost tip of the Sverdrup Bank that forms a depression to its surroundings). The northeastern basement height at 81.94°N/8.6°E (Fig. 3) shows curvilinear, non-oriented plow marks cut by several long, parallel, strictly NNW-SSE trending lineations. The random, curvilinear furrows are interpreted as derived from keels of large single icebergs. They might have been deflected by the shallowest crest of the basement height, leading to the curvilinear form of some furrows. In order to be able to rotate and turn towards a different flow direction, these icebergs must have been single ones, not trapped with others in a coherent iceberg system. The parallel, strictly NNE-SSW trending mega-scale lineations cut through the curvilinear plow marks and, therefore, must be younger. These younger lineations derive from either a single large iceberg with several deep keels or from several coherent icebergs.

The northern-to-central part of the Sverdrup Bank (81.4 to 81.6°N) shows some evidence of the same type of curvilinear furrows as on the northeastern basement height; however, these furrows are much less distinctive in these shallower areas (525 to 500 m present water depth). Further towards the center of the Sverdrup Bank (440 to 450 present water depth), these furrows cannot be observed at all. It is quite likely that icebergs with keel depths large enough to influence the northeastern basement height (with a present water depth of approximately 725 to 750 m) could barely reach the shallower central part of the Sverdrup Bank, but grounded somewhere *en route*. One of the mega-scale lineations ends exactly in the middle of one of our swath bathymetry lines in facies type 8 and clearly indicates that the corresponding iceberg came from NNE and never reached the shallower area (Fig. 5e). The southern tip of the Sverdrup Bank (at 81.1°N) apparently was not affected by younger glacial overprint; its asymmetric furrows are of tectonic origin (Geissler et al., unpubl. data).

The western basement height (81.38°N/5.55°E, 715 m to 690 m present water depth) is almost featureless on its top, similar to its surroundings towards east, north and west (facies type 7; Fig. 4h). The entire area of facies type 7 is not affected by glacigenic lineations, but shows well-layered, hemipelagic sediments, some of them associated with NNW-SSE flowing bottom currents. Water depth of this area, however, is well in the range of other areas on the Yermak Plateau that were definitely affected by iceberg keels. This leads to the interpretation that this entire area was in the lee of the elongated Sverdrup Bank that prevented icebergs from scouring. This further supports the interpretation that icebergs affecting large parts of the Yermak Plateau must have arrived from NNE heading SSW, and not vice-versa. On the eastern side of the Sverdrup

Bank, a similar area (facies type 8) is not affected by mega-scale lineations, but by strong bottom currents. However, this area is small and limited to the foot of the northeastern flank of the Sverdrup Bank. All large and deep icebergs might have grounded well before reaching this area as the one shown in Fig. 5e, further supporting the hypothesis by Kristoffersen et al. (2004) of NNE-SSW drifting icebergs.

5.5 Areas not influenced by glacigenic imprint

Along the western slope of the Yermak Plateau towards the Fram Strait and the Nansen Basin, the seafloor is not disturbed by glacigenic lineations at water depths greater than ~850 m. Echosounder profiles exhibit well-layered, hemipelagic sediments that might be deposited by parallel contour currents (Eiken and Hinz, 1993). Apparently the keels of the icebergs responsible for the mega-scale lineations on the plateau did not reach beyond 850 m present water depth. In fact, lineations are already rather sparse between 800 and 850 m present water depth.

Partially, the hemipelagic sediments of the western flank are intercalated by debris flows that derive from the upper part of the Yermak Plateau. These were quite likely caused to a large extent by icebergs that bulldozed sediment while furrowing the plateau along their NNW-SSE trending pathway, similar to the debris flows that were observed west of the Sverdrup Bank.

Along the eastern slope of the Yermak Plateau, undisturbed sediments are found mainly below 1000 to 1200 m water depth, i.e. glacigenic lineations are found at greater depth than at along the western slope. Larger icebergs that arrive from northeast would thus be trapped by the eastern slope of the Yermak Plateau, unable to pass this shallow obstacle and thus unable to reach the western slope.

6 Conclusion

Our new data show at least three major glacial events that affected the seafloor of the Yermak Plateau:

(i) a grounded ice sheet that extended at least as far north as 82°N, down to depths of more than 850 m present water depth. This grounding event is characterized by an erosional unconformity at approximately 70 to 90 m depth below seafloor (Figs. 6 and 7) and is overlain by an acoustically transparent to chaotic layer of roughly 50 m thickness interpreted as diamicton. This layer can be correlated to the overconsolidated sediments found at ODP Site 910 at a sediment depth between ~19 and 70 to 95 m. The oldest sediments just above those overconsolidated sediments were dated to the MIS19/20 boundary by Knies et al. (2007) and provide a minimum age for the grounding event.

(ii) mainly NNE-SSW trending, parallel to sub-parallel mega-scale lineations characterize large parts of the plateau west and northeast of the Sverdrup Bank in water depths between 725 and 850 m (Figs. 4 and 5). They were quite likely formed by the keels of deep-draft, megascale tabular icebergs entrapped in a coherent mass of icebergs and sea ice. Recent studies by Dowdeswell et al. (2010b) and by Jakobsson et al. (2010) suggest a MIS6 age for this younger glacigenic event; this was, however, not directly dated. A series of debris flows were found close to the Sverdrup Bank. These were quite likely caused by sediments that were bulldozed by such a coherent mass of icebergs from NNE over the Sverdrup Bank and further down its western flank. They occur at different depths within well-stratified sediments and, thus, suggest several events rather than a single one during MIS6.

(iii) in the southernmost part of our investigation area, smaller-scale curvilinear plow marks were identified at 640 to 775 m water depth. These resemble seafloor features mapped by Dowdeswell et al. (2010b) just south of where they were identified in our investigation area. Both our study and the recent study by Dowdeswell et al. (2010b) suggest single icebergs as their source, with a younger-than-MIS6 age.

At water depths greater than 850 m, the western flank of the Yermak Plateau is relatively featureless, as is the eastern flank at water depths > 1000 to 1200 m. Glacigenic overprint by single icebergs, iceberg armadas or a (grounded) ice sheet was thus limited to water depths <1200 m (not taking into account the lower sea level during the respective glacial times). This is consistent with both the study by Dowdeswell et al. (2010b) and by Vogt et al. (1994).

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Figure Captions

Fig. 1: Geographical overview of the Yermak Plateau and its surroundings. Grey arrows mark the present-day predominant surface water flows in this area (Manley et al., 1992). Spacing of bathymetry contour lines is 200 m down to 2000 m water depth and 1000 m at >2000 m water depth. Map was created from the IBCAO dataset (Jakobsson et al., 2008a) using GMT software tools (Wessel and Smith, 1991). Geographical features: FS: Fram Strait, GL: Greenland, NB: Nansen Basin, MD: Molloy Deep, SB: Sophia Basin, SA: Svalbard Archipelago, SvB: Sverdrup Bank, MS: Mosby Seamount. Currents: SpB: Spitsbergen Branch, YB: Yermak Branch, RAC: Return Atlantic Current. The white rectangle marks the area shown in Figs. 2 and 3.

Fig. 2: Overview of all data used for this study. Tracklines of seismic profiles, sediment echosounder and bathymetry data are shown in orange. Sediment echosounder details shown in Fig. 4 are marked by black lines and numbers 1 to 9, bathymetry details shown in Fig. 5 by blue rectangles and letters a to g. The seismic profiles AWI-20040020, AWI-20020415 and AWI-20040130 marked in red are shown in Fig. 6, and profiles AWI-20020388 and AWI-20020390 are presented in Fig. 7. Red stars are used to highlight ODP Leg 151 Sites 910 to 912. Note that water depths of the IBCAO map and of our high-resolution data do not always coincide.

Fig. 3: Map of the facies types found on the central and northern Yermak Plateau. Note that the prominent Sverdrup Bank elongated in N-S direction (shown here as SvB, facies type 6) forms a clear obstacle for both an ice sheet from SSW and icebergs from NNE. Red line: upper boundary of diamict layer.

Fig. 4: Sediment echosounder data of the facies types mapped in this study. Description of the facies types is given in the text. Locations of the profiles are shown in Fig. 2. The red line in c, d, and e marks the upper boundary of the diamicton. Note that the debris flows shown in (i). occur in different stratigraphical layers, with the pink being the youngest and the green being the oldest.

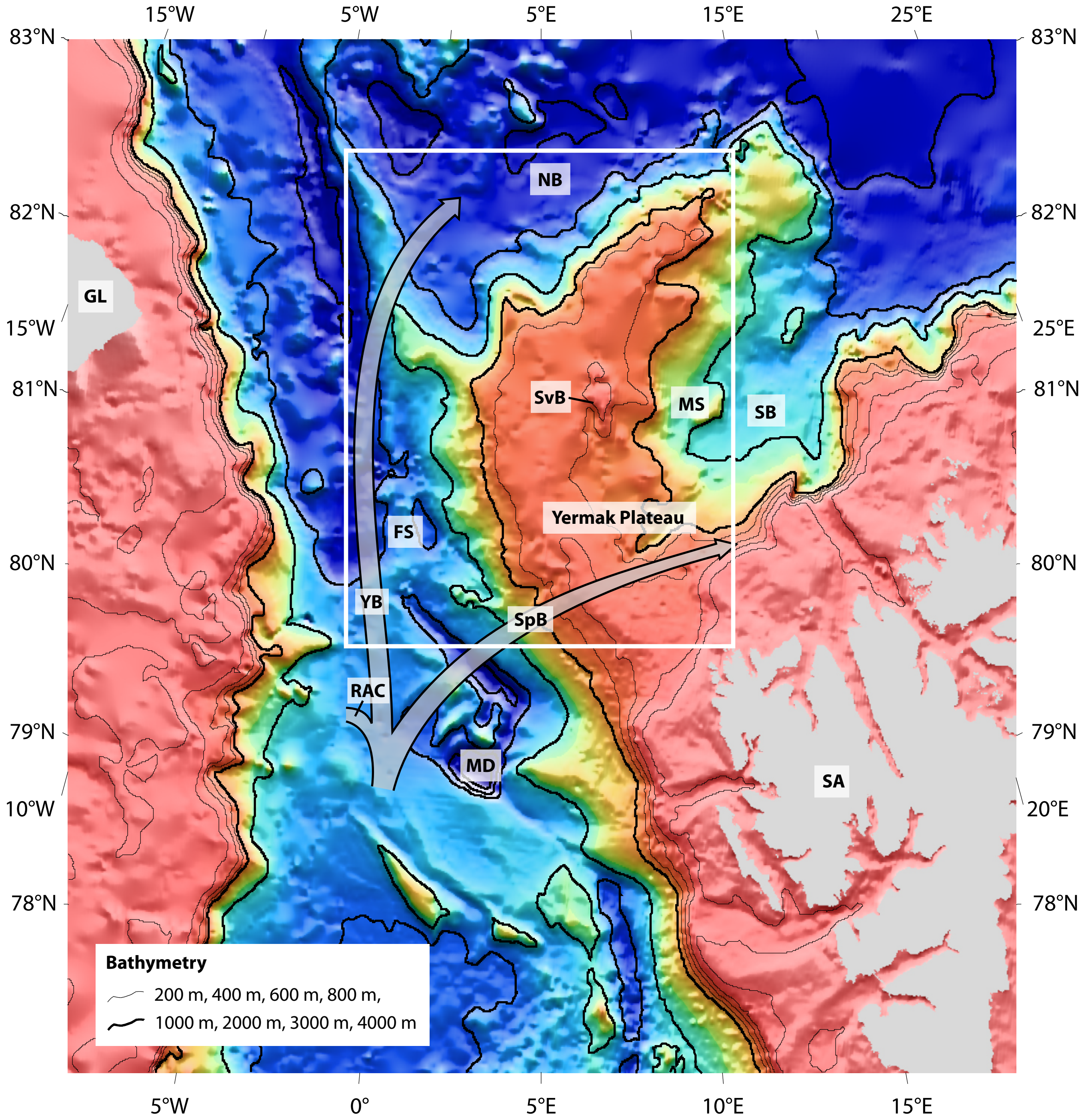
Fig. 5: Bathymetry data of the facies types mapped in this study. Description of the facies types is given in the text. Locations of the bathymetry details are shown in Fig. 2. The red arrow in e. points at the plow mark that ends abruptly east of the Sverdrup Bank.

Fig. 6: Seismic reflection and sediment echosounder profiles across the Yermak Plateau at 81.8°N (upper panel) and a more central position at 81.2°N (lower panel). Tracklines of the profiles are shown in Fig. 2. Red

arrows point at the erosional discordance below the overlaying diamicton, green arrows point at older drift sediments that were partly truncated by the erosional discordance, and blue arrows mark the position of the Sverdrup Bank. The dashed line in the lower panel marks the border between profiles AWI-20020415 and AWI-20040130.

Fig. 7: Seismic reflection profiles crossing ODP Site 910. Tracklines of the profiles are shown in Fig. 2. Profile AWI-20020390 was cut into two halves for better illustration at the red line: The northernwestern part of this profile is shown in the upper panel and continues in the lower panel with its more southeastern part. Red arrows point at the erosional discordance below the diamicton, and the orange arrow marks the western end of this discordance. The orange box between the two seismic lines at the position of ODP Leg 151 Site 910 shows the position of the overconsolidated sediment layer in the core record (between ~19 and 70 to 95 m; indicated here: 19 to 95 m). For depth-to-traveltime conversion the following acoustic velocities were used: 1750 m/s for the uppermost 19 m of the sediment, 1850 m/s for the overconsolidated section (Rack et al., 1996).

Figure 1



15°W
5°W
5°E
15°E
25°E
83°N
82°N
81°N
80°N
79°N
78°N
15°W
10°W
25°E
20°E
5°W
0°
5°E
10°E
15°E
GL
NB
SvB
MS
SB
Yermak Plateau
FS
YB
SpB
RAC
MD
SA
Bathymetry
200 m, 400 m, 600 m, 800 m,
1000 m, 2000 m, 3000 m, 4000 m

Figure 2

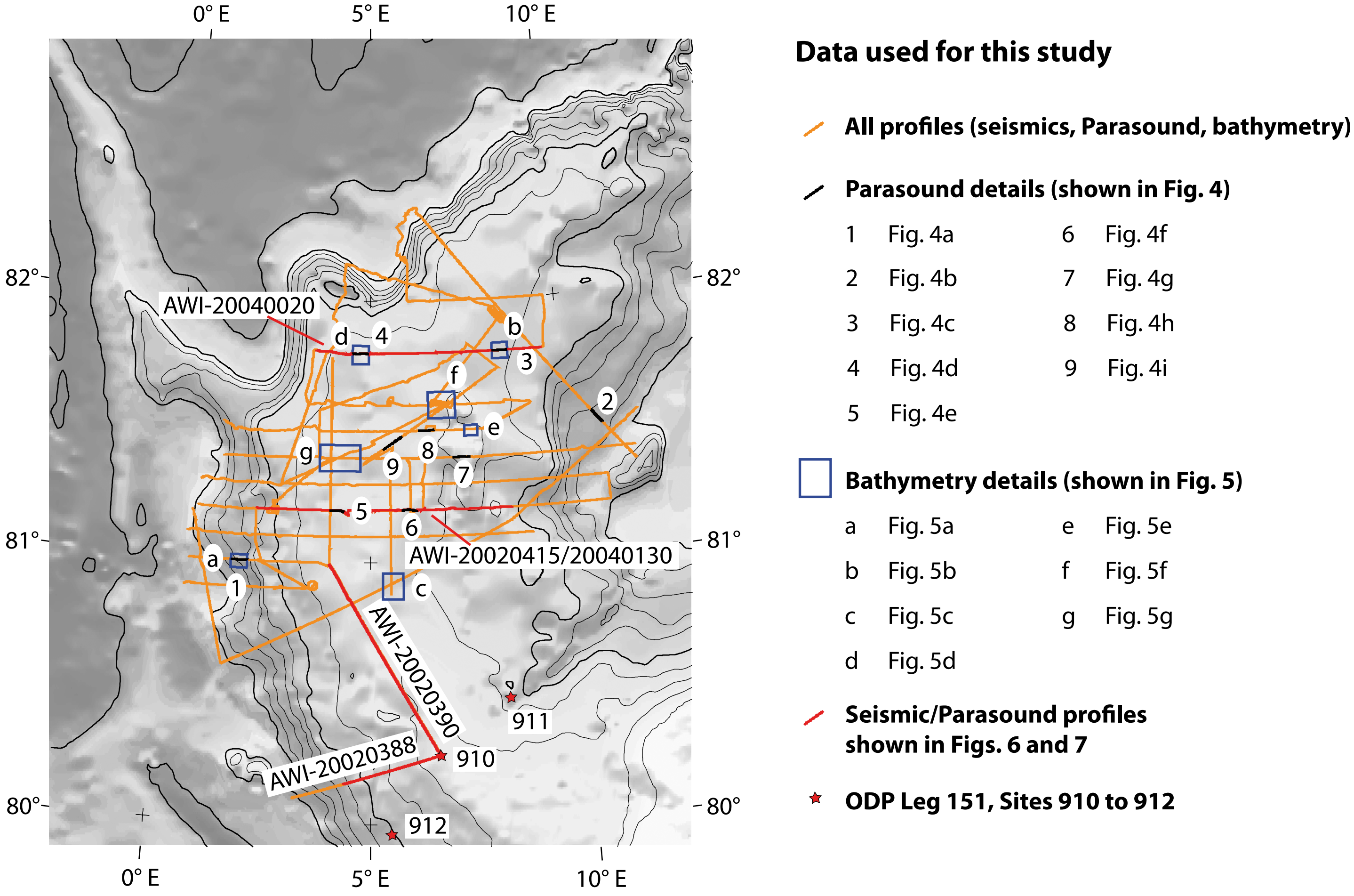
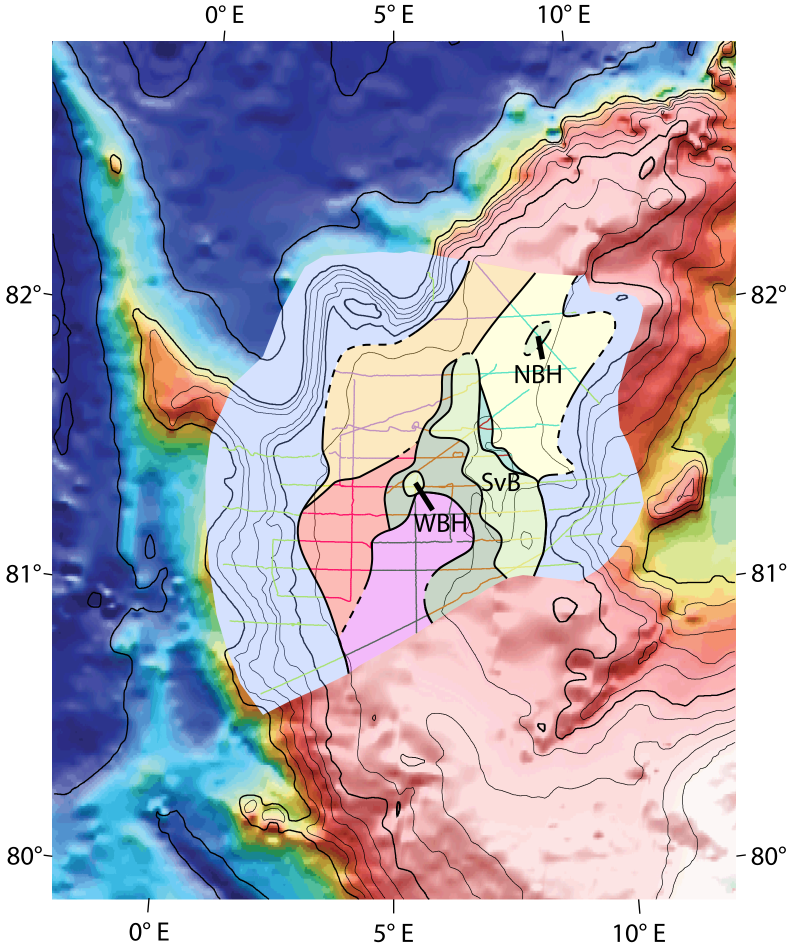

0° E
5° E
10° E
82°
81°
80°
AWI-20040020
AWI-20020415/20040130
AWI-20020390
AWI-20020388
910
911
912
Data used for this study
All profiles (seismics, Parasound, bathymetry)
Parasound details (shown in Fig. 4)
1 Fig. 4a
2 Fig. 4b
3 Fig. 4c
4 Fig. 4d
5 Fig. 4e
6 Fig. 4f
7 Fig. 4g
8 Fig. 4h
9 Fig. 4i
Bathymetry details (shown in Fig. 5)
a Fig. 5a
b Fig. 5b
c Fig. 5c
d Fig. 5d
e Fig. 5e
f Fig. 5f
g Fig. 5g
Seismic/Parasound profiles shown in Figs. 6 and 7
ODP Leg 151, Sites 910 to 912

Figure 3



Facies types on the Yermak Plateau

Flanks of the Yermak Plateau

1 well-layered (drift) sediments

Glaciogenic features on the Yermak Plateau

2 NNE-SSW mega-scale flutes with 15 to 25 m sediment cover

3 NNE-SSW mega-scale flutes with 10 to 15 m cover

4 NNE-SSW/NNW-SSE mega-scale flutes with 5 to 10 m sediment cover

5 Irregularly oriented ploughmarks with less than 5 m sediment cover

Basement height and associated landforms

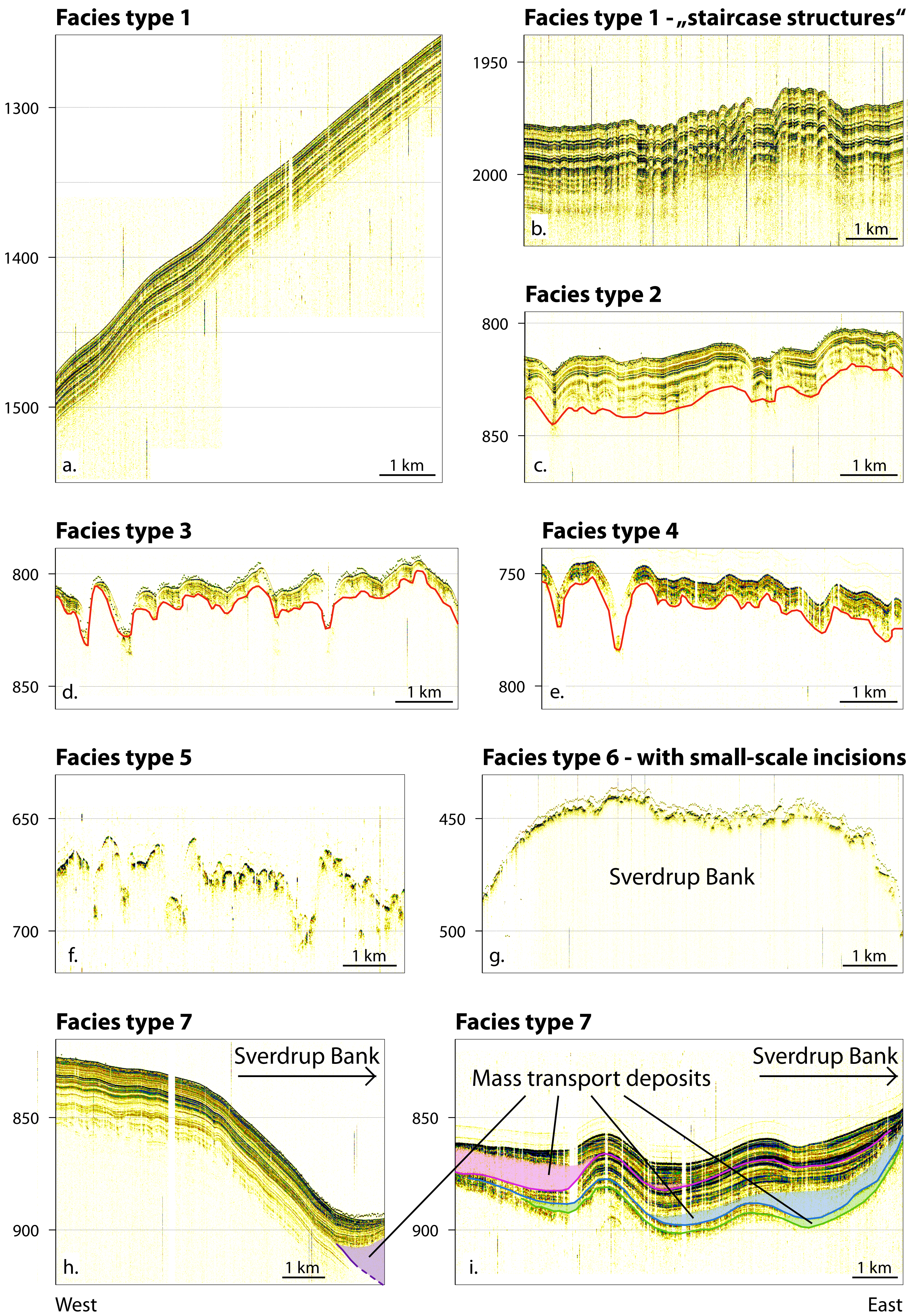
6 basement heights with little or no sediment cover

7 drift sediments on western foot of basement heights

8 contourite sediments on eastern foot of basement heights

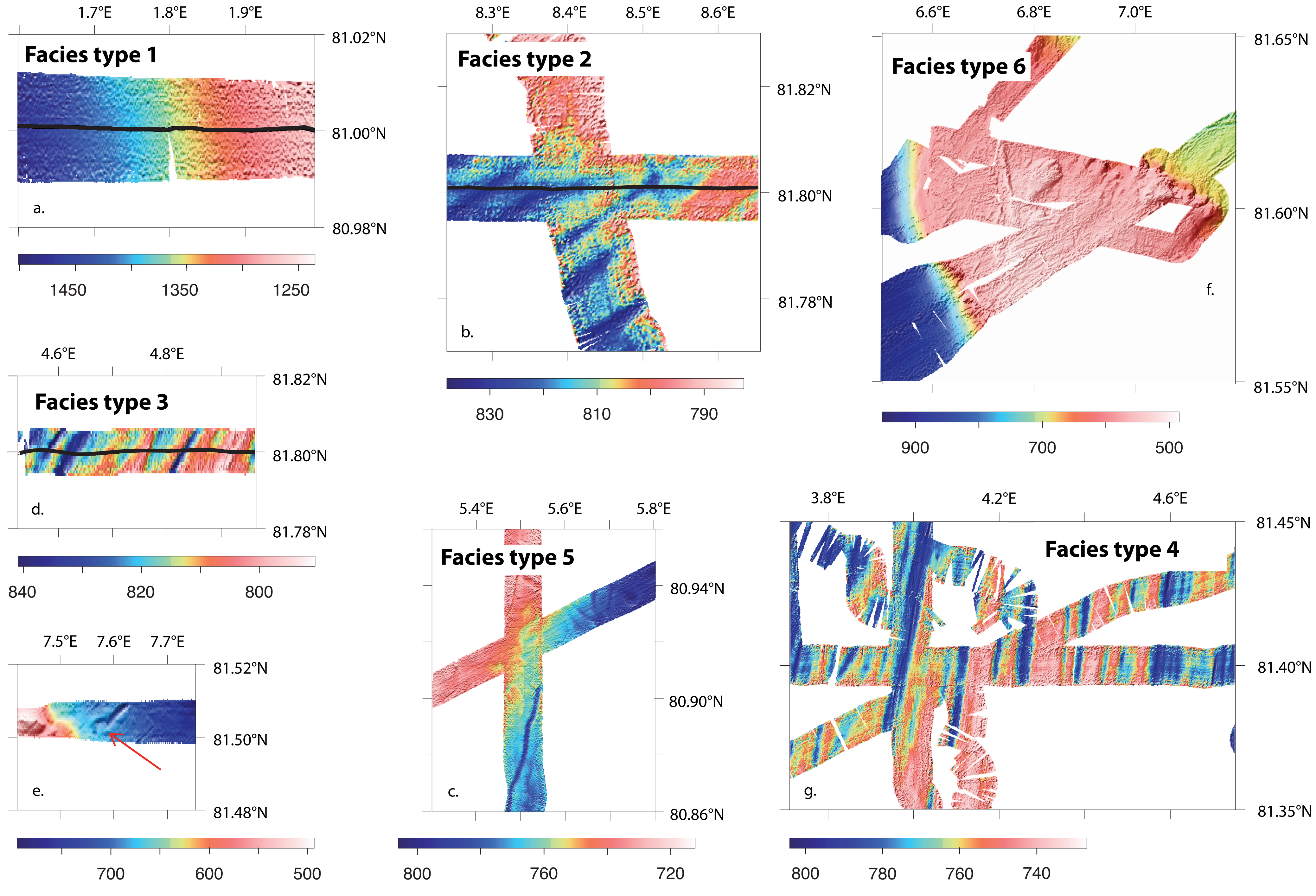
SvB Sverdrup Bank
NBH northeastern basement height
WBH western basement height

Figure 4



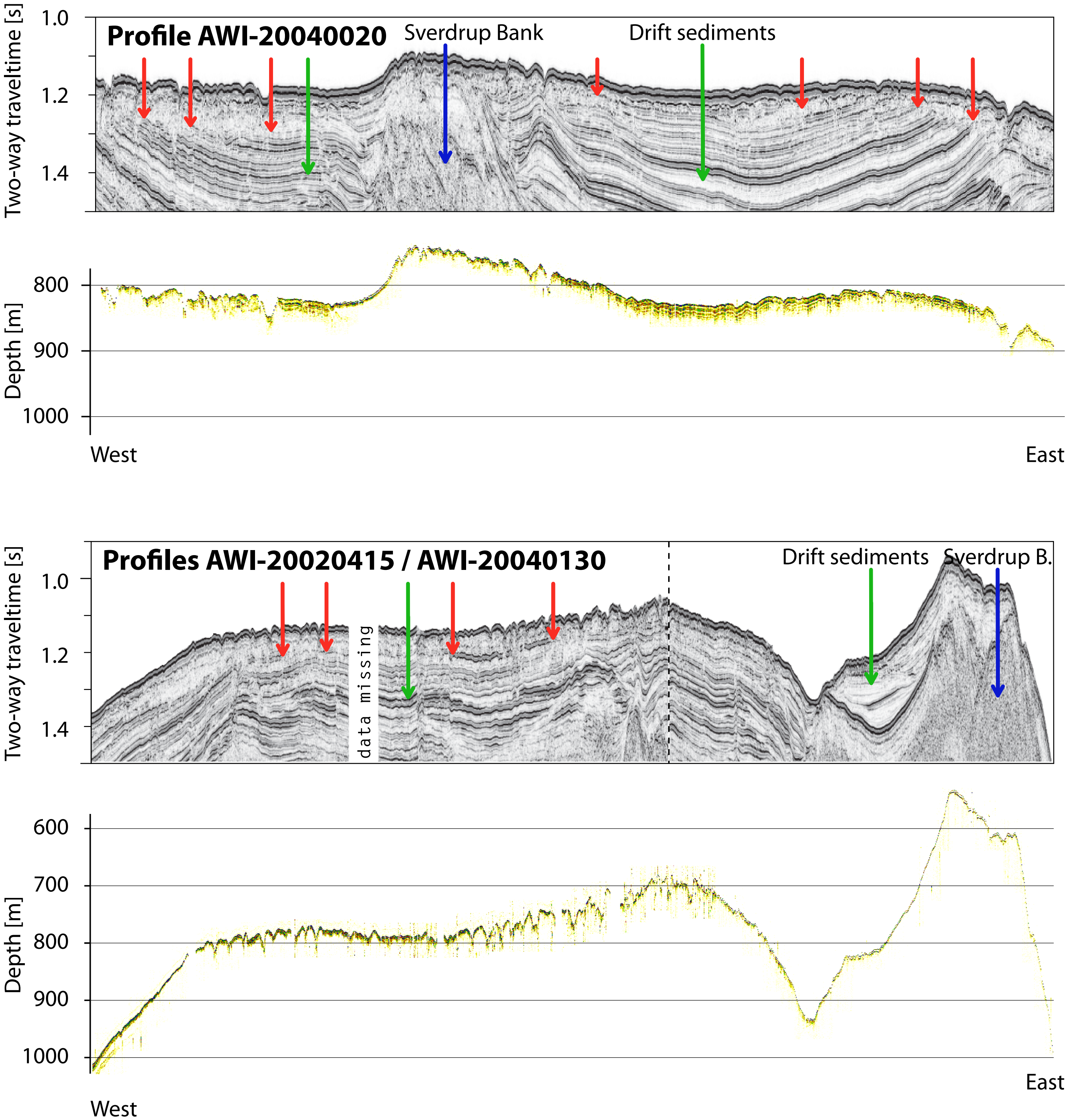
Facies type 1
1300
1400
1500
a.
1 km
Facies type 1 - „staircase structures“
1950
2000
b.
1 km
Facies type 2
800
850
c.
1 km
Facies type 3
800
850
d.
1 km
Facies type 4
750
800
e.
1 km
Facies type 5
650
700
f.
1 km
Facies type 6 - with small-scale incisions
450
Sverdrup Bank
500
g.
1 km
Facies type 7
Sverdrup Bank
850
900
h.
1 km
Facies type 7
Mass transport deposits
Sverdrup Bank
850
900
i.
1 km
West
East

Figure 5



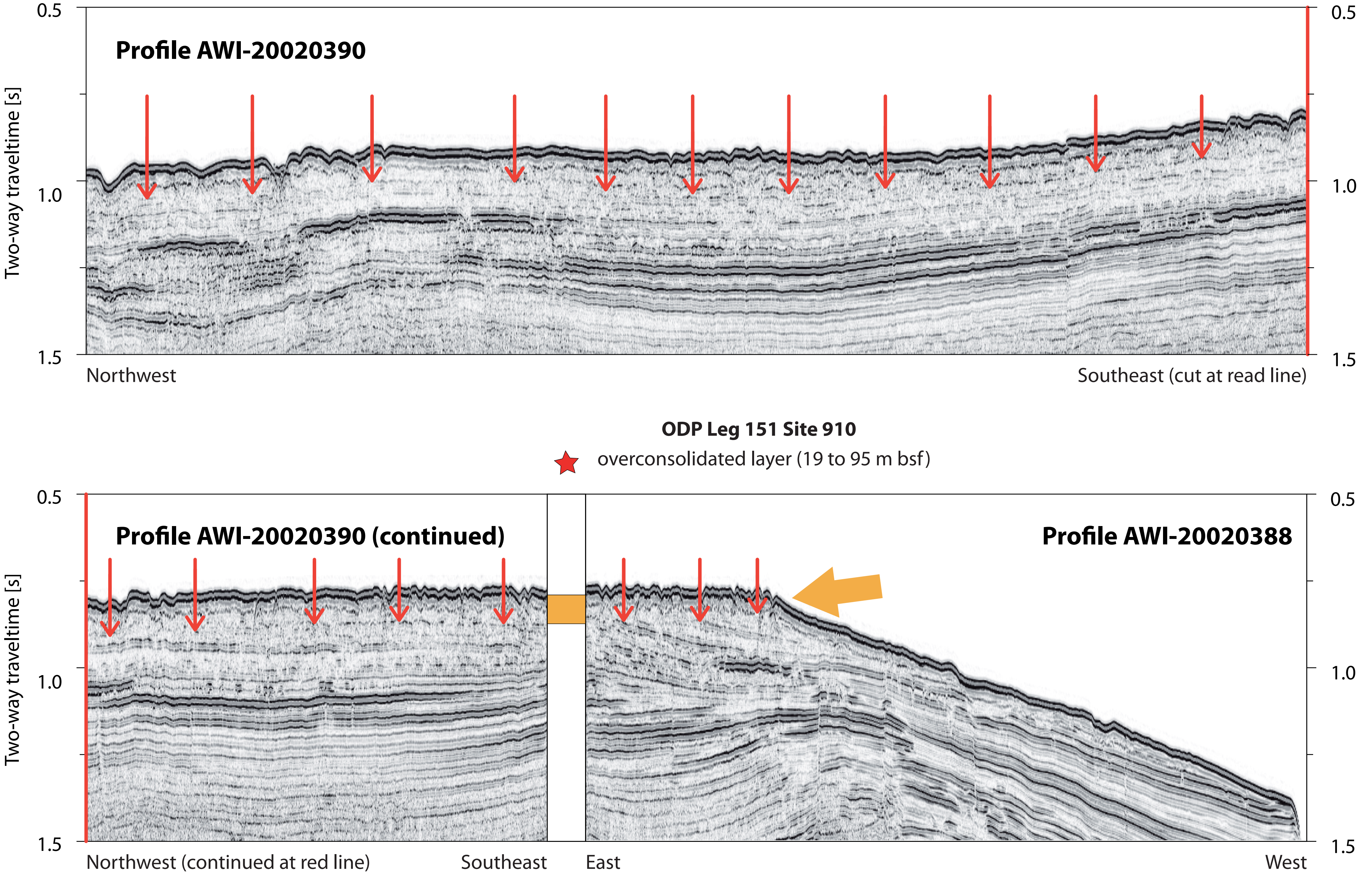
Facies type 1
1.7°E
1.8°E
1.9°E
81.02°N
81.00°N
80.98°N
a.
1450
1350
1250
Facies type 2
8.3°E
8.4°E
8.5°E
8.6°E
81.82°N
81.80°N
81.78°N
b.
830
810
790
Facies type 6
6.6°E
6.8°E
7.0°E
81.65°N
81.60°N
81.55°N
f.
900
700
500
Facies type 3
4.6°E
4.8°E
81.82°N
81.80°N
81.78°N
d.
840
820
800
7.5°E
7.6°E
7.7°E
81.52°N
81.50°N
81.48°N
e.
700
600
500
Facies type 5
5.4°E
5.6°E
5.8°E
80.94°N
80.90°N
80.86°N
c.
800
760
720
Facies type 4
3.8°E
4.2°E
4.6°E
81.45°N
81.40°N
81.35°N
g.
800
780
760
740

Figure 6



Profile AWI-20040020
Sverdrup Bank
Drift sediments
Two-way traveltime [s]
1.0
1.2
1.4
Depth [m]
800
900
1000
West
East
Profiles AWI-20020415 / AWI-20040130
data missing
Drift sediments
Sverdrup B.
Two-way traveltime [s]
1.0
1.2
1.4
Depth [m]
600
700
800
900
1000
East
West

Figure 7



Profile AWI-20020390
0.5
1.0
1.5
Two-way traveltime [s]
Northwest
Southeast (cut at read line)
ODP Leg 151 Site 910
overconsolidated layer (19 to 95 m bsf)
Profile AWI-20020390 (continued)
Profile AWI-20020388
Northwest (continued at red line)
Southeast
East
West