DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2005/71

Late Quaternary sedimentation patterns offshore West Greenland based on magnetic susceptibility profiles

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MINISTRY OF THE ENVIRONMENT

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Introduction and objective

Studies of the offshore region, West Greenland, are important in order to mature new areas for hydrocarbon exploration. For future planning of wells, production facilities and infrastructure for transporting hydrocarbons out of the area a regional knowledge and understanding of the sub-recent and recent geological hazards is required. The objective of this study is to gain information on the sedimentation pattern and stratigraphy of the shallow deposits in the region.

A detailed geohazard study offshore West Greenland was carried out in 2001 (Nielsen *et al.* 2001) build on a previous pilot project (Nielsen *et al.* 2000). Sediment cores from these studies are only presented from the previous Fylla license area, though not placed in a stratigraphic framework. The present study adds to the previous investigations by focusing on the detailed stratigraphy of the uppermost sediment package as well as including sediment cores from a broader area (Fig. 1).

Study area

Modern oceanography

The surface circulation off the margin of West Greenland is characterised by the northward flowing relatively warm (2°–6°C) West Greenland Current (WGC), which consists of a mixture of the East Greenland and Irminger Current. A branch of the WGC turns west at the Davis Strait and merges with the cold southward flowing Baffin Land Current and forms the Labrador Current. The WGC is displaced southward during winters where the cold Baffin Land Current dominates most of the Labrador Sea north of the Hudson Strait (Coachman & Aagaard 1974).

Late Quaternary Marine Stratigraphy

Late Quaternary Labrador Sea sediments have proven typified by pulses of coarse layers rich in ice-rafted detrital carbonate interlayered with hemipelagic sediments. These layers can reach thickness' up to 1 m in the NW Labrador Sea whereas they are thinner towards east (e.g. Aksu & Mudie 1985; Rashid *et al.* 2003). The events causing the layers can be correlated to periods when massive discharges of icebergs occurred in the North Atlantic (Heinrich events (H-events)) (Heinrich 1988; Bond *et al.* 1992). The icebergs origin mainly from collapses of the Laurentide Ice Sheet (Alley & MacAyeal 1994) but also discharges from the Greenland and Fennoscandic ice caps contributed considerable (Bond & Lotti 1995; Fronval *et al.* 1995). The H-events occurred every 5–7 ka (x 1000 years) during the last glacial (see Table 1) and had a duration around 0.8–1.7 ka (e.g. Bond & Lotti 1995; Elliot *et al.* 2001) causing dramatic oceanographic changes: lowered sea surface salinity, reduced sea surface temperature and a reduced formation of North Atlantic Deep Waters in the North Atlantic (Cortijo *et al.* 1997; Vidal *et al.* 1997; Elliot *et al.* 2001).

The H-layers as well as the intervening small-scale ice-rafted debris (IRD) deposits correlates to the large amplitude atmospheric temperature oscillations recorded in the Greenland ice cores, the Dansgaard-Oeschger oscillations (Dansgaard *et al.* 1993; Bond *et al.* 1997; Andrews & Barber 2002). Thus H-events coincided with extreme cooling periods that lasted up to several hundreds of years as shown in the ice cores.

		Age (ka)	Standard deviation (ka)	Duration (ka)
H1	Base	15.1	0.7	1.6
	Top	13.4	0.3	
H2	Base	22.1	0.8	1.7
	Top	20.4	0.1	
H3	Base	27.4	1.6	1.3
	Top	26.1	0.6	
H4	Base	34.9	1.1	0.8
	Top	33.9	0.7	

Table 1. Average age and duration of Heinrich events 1–4 from the North Atlantic (Elliot *et al.* 2001).

Material and methods

Sediment cores

Sediment cores collected on three different cruises have been included in this study (Table 2). Gravity cores from the Fylla area were collected in 1998 as part of a survey for STATOIL including the 47 cores used for this study (See Nielsen *et al.* 2000). The upper 5 cm of these cores was removed for environmental studies before the magnetic susceptibility measurements were carried out. During the cruise with R/V Professor Logachev in 2003, a number of gravity and vibro cores were taken (Dalhoff *et al.* 2003). For this study, cores from Seep area C and D, Davis Strait High and Canyon A have been selected. From the latter areas, additional piston and gravity cores from a cruise with R/V DANA in 2004 have also been included, as well as cores from Seep F and E.

One third of the cores included in this study have been opened and sedimentological described (See Table 2). The sedimentological logs as well as photographs of cores from the TTR13 cruise in 2003 can be found in Dalhoff *et al*. (2003) and descriptions of Fylla cores in Nielsen *et al*. (2000).

Core no.	Area	Figure (transect)	Water depth (m)	Core length (m)	Core description
DANA04-06G	Seep C	6	976	1,35	
DANA04-08G	Seep C	6	985,47	5,43	
DANA04-09G	Seep C	6	972,67	4,43	
DANA04-13G	Seep F	6	1380	5,46	
DANA04-14G	Seep F	6	1422	5,37	
DANA04-15G	Seep E	6	1764	1,75	
DANA04-16P	Seep E	6	1737	8,18	
DANA04-21G	Canyon A	6	1577	3,31	
DANA04-35G	Canyon A	6	2269	5,08	
TTR13-AT-455G	Canyon A	6	2381	5,54	x
TTR13-AT-462G	Davis Strait High	6	605	1,62	x
TTR13-AT-464v	Davis Strait High	6	677	1,10	x
TTR13-AT-467G	Seep D	6	793	1,38	x
TTR13-AT-468G	Seep D	6	718	0,61	x
TTR13-AT-469G	Seep D	6	727	0,56	x
TTR13-AT-470G	Seep D	6	793	0,52	x
TTR13-AT-471G	Seep D	6	697	0,42	x
TTR13-AT-473G	Seep C	6	1063	4,40	x
TTR13-AT-474G	Seep C	6	1032	4,87	x
TTR13-AT-475G	Seep C	6	1020	3,55	x
TTR13-AT-476G	Seep C	6	1006	2,80	x
TTR13-AT-477G	Seep C	6	1007	2,90	
TTR13-AT-478G	Seep C	6	1019	5,50	
TTR13-AT-479G	Seep C	6	1033	6,00	
TTR13-AT-480G	Seep C	6	1045	3,20	
TTR13-AT-481G	Seep C	6	1058	2,20	
Fylla-GC98 02	Fylla A	3 (3)	1155	1,86	
Fylla-GC98 03*	Fylla A	3 (1B)	1160	2,92	x
Fylla-GC98 04	Fylla A	3 (1B)	1161	2,60	
Fylla-GC98 05	Fylla B	4 (1A)	1170	2,75	x
Fylla-GC98 06	Fylla B	4 (1A)	1175	0,97	
Fylla-GC98 08	Fylla B	4 (1A)	1180	2,86	x
Fylla-GC98 09	Fylla A	3 (1B)	1154	1,67	
Fylla-GC98 10	Fylla A	3 (1B)	1166	1,60	x
Fylla-GC98 11	Fylla A	3 (2)	1178	1,88	x
Fylla-GC98 12	Fylla A	3 (2)	1160	2,65	x
Fylla-GC98 13	Fylla A	3 (3)	1155	2,59	x

Fylla-GC98 14	Fylla A	3 (1B)	1155	1,60	
Fylla-GC98 15	Fylla A	3 (2)	1170	0,60	
Fylla-GC98 20	Fylla A	3 (2)	1157	1,42	
Fylla-GC98 21	Fylla A	3 (3)	1156	2,50	x
Fylla-GC98 22	Fylla A	3 (1B)	1225	1,81	
Fylla-GC98 23	Fylla A	3 (1B)	1219	2,86	
Fylla-GC98 24	Fylla A	3 (1B)	1198	2,95	x
Fylla-GC98 25	Fylla A	3 (1B)	1219	2,92	
Fylla-GC98 26	Fylla A	3 (1B)	1243	2,67	x
Fylla-GC98 27	Fylla A	3 (1B)	1193	2,84	
Fylla-GC98 28	Fylla A	3 (1B)	1157	2,34	
Fylla-GC98 29	Fylla B	4 & 5 (1A & 6)	1170	1,50	
Fylla-GC98 32	Fylla B	4 (1A)	1172	1,08	
Fylla-GC98 34	Fylla B	4 (4)	1172	1,00	
Fylla-GC98 35	Fylla B	4 (1A)	1185	1,13	
Fylla-GC98 36	Fylla B	4 & 5 (1A & 6)	1168	2,73	x
Fylla-GC98 37	Fylla B	4 (4)	1167	2,20	
Fylla-GC98 39	Fylla B	4 (1A)	1186	1,08	
Fylla-GC98 40	Fylla B	4 (1A)	1175	1,13	
Fylla-GC98 41	Fylla B	4 (4)	1163	0,95	
Fylla-GC98 43	Fylla B	4 & 5 (4 & 6)	1167	2,27	
Fylla-GC98 44	Fylla B	5 (6)	1205	1,36	
Fylla-GC98 46	Fylla B	5 (6)	1224	2,80	
Fylla-GC98 47*	Fylla B	5 (6)	1231	2,66	x
Fylla-GC98 48	Fylla B	5 (6)	1207	1,21	
Fylla-GC98 49	Fylla B	5 (6)	1195	0,95	
Fylla-GC98 50	Fylla B	4 & 5 (5 & 6)	1181	2,73	x
Fylla-GC98 51	Fylla B	4 (5)	1196	1,13	x
Fylla-GC98 52	Fylla B	4 (5)	1190	2,05	
Fylla-GC98 53	Fylla B	4 & 5 (5 & 6)	1180	2,67	
Fylla-GC98 54	Fylla B	4 (5)	1179	2,91	x
Fylla-GC98 55	Fylla B	4 (5)	1181	1,90	
Fylla-GC98 56	Fylla B	4 (5)	1189	2,21	
Fylla-GC98 57	Fylla B	4 (5)	1192	0,79	
Fylla-GC98 58	Fylla B	4 & 5 (5 & 6)	1182	1,17	

Table 2. Core data (core positions, water depth and recovery). *Dated cores.

Magnetic susceptibility

The majority of the cores were measured as whole-core without being opened, using a Barington core logger type MS2C (For details on the measurements of the Fylla cores see (For details on the measurements of the Fylla cores see Nielsen *et al.* 2000). The following cores: TTR13-AT-455G, -462G, -464v, -467G, -468G, -469G, -470G, -471G, -473G, -474G, -475G and -476G were measured onboard the research vessel by use of a Barington Instruments Magnetic Susceptibility meter with a MS2E1 probe. All cores from the cruise with DANA in 2004 have been cut in 1 m sections and sampled in the bottom of each section before magnetic susceptibility measurements were carried out. Hence, low values at the beginning of each core section might be an artifact and not naturally caused.

Magnetic susceptibility is a non-destructive method that can be carried out without opening the cores. This method has proved to be very successful to correlate cores within the same sedimentary system (e.g. Andrews & Stravers 1993; Elliot *et al.* 2001; Moros *et al.* 2002). Magnetic susceptibility measurements of hemipelagic and glacial marine sediments is principally a measure of the concentration of ferrimagnetic minerals in the sediment, but can also be affected by mineral input of calcite, dolomite, quarts as well as organic carbon and by changes in grain-size.

AMS ^{14}C dating

In order to place the sediment cores into a stratigraphic frame work four AMS ^{14}C datings have been performed on cores from the Fylla and Seep D area. To provide the required sample weight of minimum 8 mg more than 1000 planktic foraminifera of the species *neogloboquadrina pachyderma* sinistral were picked. All dates in the following text referred to as *ka* (x 1000 years) are uncalibrated ^{14}C years BP (before present (1950)) and corrected for a standard reservoir age of 400 years.

Results and interpretation

AMS ^{14}C dating

The results of AMS ^{14}C dates are shown in Table 3.

Core no.	Dated core level[a]	Reservoir corrected age[b]	^{14}C Lab no.
TTR13-AT-467G	0.64-0.65	15.640 +/-90	KIA 23367
TTR13-AT-469G	0.42-0.43	17.100 +/-100	KIA 23368
Fylla GC 9803	1.82-1.84	28.510 +380/-360	KIA 24514
Fylla GC 9847	2.36-2.37	>49.050	KIA 24515

Table 3. AMS ^{14}C dates. [a] m below core top, [b] ^{14}C years BP, assuming a 400 year reservoir age.

Magnetic susceptibility

Comparisons of core descriptions and magnetic susceptibility profiles have been possible for a number of cores from the Fylla area as well as core from the TTR13 cruise in 2003 (Nielsen *et al.* 2000; Dalhoff *et al.* 2003). In general, high magnetic susceptibility signals are seen mainly in coarse-grained layers, though less pronounced in the Fylla area. Thus, increasing grain sizes and possibly the lithologic composition of the coarser grains mainly controls the magnetic susceptibility signal in this region. Scattered occurrences of pebbles through the cores are referred to as dropstones.

In the following, results and interpretations of the magnetic susceptibility profiles from each locality will be presented. Locality names and core locations are shown on Figure 1 and 2.

Fylla area

Results. The very densely sampled area with 46 short cores has enabled a consistent stratigraphy of the upper sediment package (upper 3 m). The locations of the cores are clustered in two areas, named Fylla A and Fylla B. The cores are projected into six transect lines including one connecting the two area (See Figs 2–5). In general, the two areas show high similarities regarding magnetic susceptibility profiles especially within each area, as well as between areas. Comparisons of magnetic susceptibility signals with the core descriptions are possible for 15 cores showing that high magnetic susceptibility values only in some cases are visible due to change in grain size.
Two AMS ^{14}C measurements have been carried out in cores from Fylla A and Fylla B, respectively, suggesting ages within the last glacial (within Marine Isotope Stage 3).

Interpretation. The striking seesaw pattern with high magnetic susceptibility values corresponding to intervals with coarser sediment is a known pattern of marine sediments of glacial age from the Baffin Bay and Labrador Sea (e.g. Andrews *et al.* 1998; Andrews & Barber 2002; Rashid *et al.* 2003). The coarse layers formed in periods with increased transport of icebergs from the Laurentide ice sheet and thus increased input of ice-rafted debris to the sea floor. Similarly, the AMS ^{14}C date in core GC 98-03 at 28.5 ka BP just predates H-event 3 (H3, see Table 1), suggesting that the high magnetic susceptibility signal above this level most likely belong to H3 (Fig. 3). The pronounced high magnetic susceptibility signals below and above could possibly be correlated to H4, H2 and H1. For the Fylla A area this implies sedimentation rates of 6–9 cm/ka above H3, assuming the top of the core to be recent, which correspond to glacial sedimentation rates found further south (e.g., 10 cm/ka, Stoner *et al.* 1995). However, the upper 5 cm of the cores was removed before magnetic susceptibility measurements were carried so the upper Holocene must be missing. That part or most of the Holocene deposits are missing is also suggested by the lack of constant low values in the top of cores (Andrews & Stravers 1993). The maximum sedimentation rates of Fylla A would increase to 15 cm/ka if assuming the Holocene is missing.
Correlation of the H3 signal can be made from the Fylla A to the Fylla B area. In addition, the oldest stratigraphic level in the latter area is predated to H5 by AMS ^{14}C data from core GC 98-47 (See Table 1–2).
Sedimentation rates in the Fylla B area vary between 5–7 cm/ka if the Holocene is complete and 8–10 cm if the Holocene is lacking, thus slightly lower than in Fylla A.

The presence of H-layers in all the longest cores implies that the iceberg drift during the H-events influenced the whole area.

Canyon A

Results. Three cores from the Canyon A area are included in this study (see Fig. 6). Core DANA04-21G from 1577 m water depth displays a magnetic susceptibility pattern similar to the patterns seen in the Fylla A area. No core description is present from this core. The two other cores are taken from water depths larger than 2250 m and have rather uniform magnetic susceptibility profiles due to the very homogeneous lithology (i.e. core description of TTR13-AT-455G).

Interpretation. The magnetic susceptibility profiles of core DANA04-21G and core Fylla 98-53 correlate nicely and suggest at least the presence of H4 up to H2 implying sedimentation rates of min. 6 cm/ka. Thus, deposition of IRD layers superimposed on the hemipelagic sedimentation also occurred in this area. However, such patterns are not recognised in the two cores from greater water depths in Canyon A and hinder correlation to any of the other cores. Possibly, because the sedimentation in the deeper part of the canyon is controlled by bottom currents as known from the North Atlantic (Kissel *et al.* 1997) and dilute any IRD signals.

Seep area C

Results. The magnetic profiles from cores retrieved in the Seep C area cluster in two groups with different patterns (Fig. 6). Cores TTR13-AT-473G, -474G, -475G and 476G have very irregular magnetic susceptibility profiles with high values corresponding to coarse grained sediment (see core logs in Dalhoff *et al.* 2003).

None of the remaining cores have been opened and thus no core descriptions exist. The magnetic susceptibility profiles of these cores reveal much more smooth patterns as known from the other areas, e.g. Fylla, Seep E and F.

Interpretation. Though all the cores are from intermediate water depth and closely located a correlation between cores are not straightforward. The southernmost cores, with a smooth fluctuating magnetic susceptibility pattern can be correlated internally and to the Fylla A area (e.g. core Fylla 98-47, Fig. 4). This suggests presence of H4 and H3 and possibly younger H-layers as well. Sedimentation rates in Seep C will then be between 4 and 5 cm/ka. Correlation further northward is tentative and further stratigraphic framework is not possible to base only on the magnetic susceptibility profiles.

Seep area D

Results. The four short cores (around 50 cm long) from Seep area D have general similarities in the magnetic susceptibility profiles with higher values in the lower part of the cores. The high values correspond to intervals with high concentrations of pebbles and gravel. Correlation between cores is based on both the magnetic susceptibility profiles as well as the sedimentological logs. An interval rich in pebbles is also found in the fifth core from the area TTR13-AT-467G, however, the interval here show relatively low values in magnetic susceptibility. If this coarse interval correspond to the one found in the other

cores, the low magnetic susceptibility values might be due to a lower concentration of pebbles compared to the other coarse intervals, or to a larger detrital carbonate fraction.
The coarse level in core TTR13-AT-467G is dated to 15.6 ka BP (see Table 3). Correspondingly, a ^{14}C date in the coarse layer in core TTR13-AT-469G suggest late glacial ages as well, i.e. 17.1 ka BP.

Interpretation. Based on the AMS ^{14}C date just below the coarse grained interval in core TTR13-AT-467G it is suggested that this interval correspond to the coarse grained interval in the short cores, though diverging magnetic susceptibility values. Thus, continuous hemipelagic sedimentation has occurred since the Last Glacial Maximum.
Analyses of diatoms in core TTR13-AT-467G reveals a typical polar assemblage between 100 and 60 cm as well as in the upper 20 cm (K.G. Jensen, personal communication 2005). The intervals between, including the coarse grained interval, contain no diatoms. This could be explained by rapid sedimentation like during the Heinrich event 1, as part of the final collapse of the Laurentide ice sheet (Andrews *et al.* 1995) resulting in large iceberg discharge into the Labrador Sea, Baffin Bay area.
The diatom floras in the level below indicate more oceanic (Atlantic?) conditions with less sea ice compared to the upper Holocene flora, which show a higher influence of the East Greenland Current (K.G. Jensen, personal communication 2005).

Davis Strait High

Results.
Only two cores have been retrieved from the Davis Strait High area, eastern and western side, respectively. The magnetic profiles of the two cores are very fluctuating and cannot be correlated. This is likely explained by the very different lithology. Core TTR13-AT-462G from the western side of the high consists of a succession of sandy and clayey layers with dropstones occurring throughout. A completely different sedimentation pattern is seen in core TTR13-AT-464v from the eastern part of the area with a gradual decrease in grain size from angular and rounded pebbles (up to 4 cm) in a clayey sandy-silty matrix to coarse sand in the upper part.

Interpretation. The sediment represented in core TTR13-AT-462G suggests a continuous hemipelagic deposition with intervals of increased input of ice-rafted debris (IRD). The peak in magnetic susceptibility in the upper part of the core corresponds to a sand layer in the core and could be deposited during an H-event, possibly H1. In that case it could be speculated that the structureless silty clay interval between 105 and 86 cm possibly indicating periods with more dense ice cover corresponds to the Last Glacial Maximum.
The very coarse material in the bottom of core TTR13-AT-464v and the following pronounced fining upward sequence indicate a different deposition pattern than TTR13-AT-462G possibly a fast deposition by sediment-gravity flows.

Seep area E and F

Results. Seep area E and F are the southernmost included in this study situated at the slope towards the deep Labrador Sea. A correlation between the two cores from the respective areas can have been made, though only tentative. None of the cores have been opened and described (Fig. 6).

Interpretation. The magnetic susceptibility profiles show similar patterns seen further north, however, direct correlations based only on the magnetic susceptibility profiles are difficult. A speculative correlation could be between core DANA04-21G from Canyon A to Core DANA04-16P, suggesting the presence of H4 to H2. In that case, sedimentation rates would be around 6 cm/ka.

Regional sedimentation patterns

Based on the magnetic susceptibility profiles, AMS^{14}C dates and core descriptions it has been possible to relate the study areas into the known event stratigraphy (see Table 4). In general, cores from intermediate water depths (all areas except Seep D and Davis Strait High) contain evidence of hemipelagic sedimentation interlayered with IRD-rich Heinrich layers. Hence, this pattern is found in all of the studied areas suggesting that no reorganisation of the upper sediments have occurred after deposition.

The oldest stratigraphic layers are reached in Fylla B. The Davis Strait High and Seep C areas with water depths around 600 m show similar sedimentation patterns. The oldest stratigraphic levels reached in these areas are from the Last Glacial Maximum (LGM). Indication of a possible mass flow deposit is only found in one core from the Davis Strait High at 600 m water depth.

	H5	H4	H3	H2	LGM	H1	Holocene	Sedimentation rates (cm/ka)
Fylla A	? --	--------	--------	--------	----------	- - -?		5–7
Fylla B		--------	--------	--------	---------	- - -?		6–9
Seep C		--------	--------	--------	- ?			4–5
Seep D					? - - -	--------	----?	2–4
Seep E		- - - - -	- - - - -	- - - - -	-?			~6
Seep F		- - - - -	- - - - -	- - - - -	-?			~6
Canyon A		--------	--------	- - -				~6
Davis Strait High					? - - -	- - - - -	- - ?	~2

Table 4. Stratigraphic levels found in the studied areas. Interpreted presence of Heinrich layers (H) is marked by --- and more speculative interpretations marked by - - -. Sedimentation rates (cm/ka) are based on AMS^{14}C dates and correlation of interpreted H-layers.

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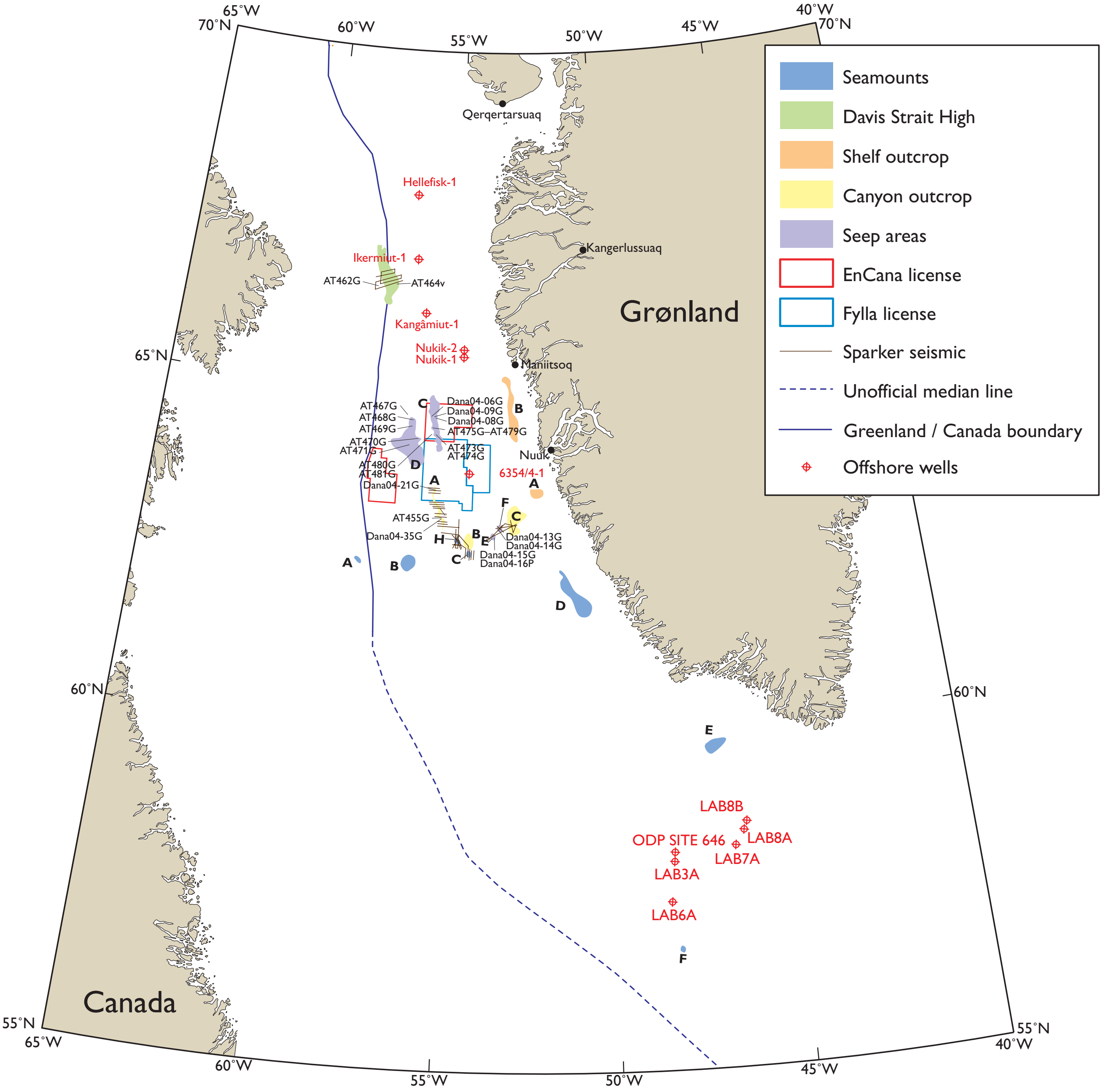

Fig. 1. Map of study area

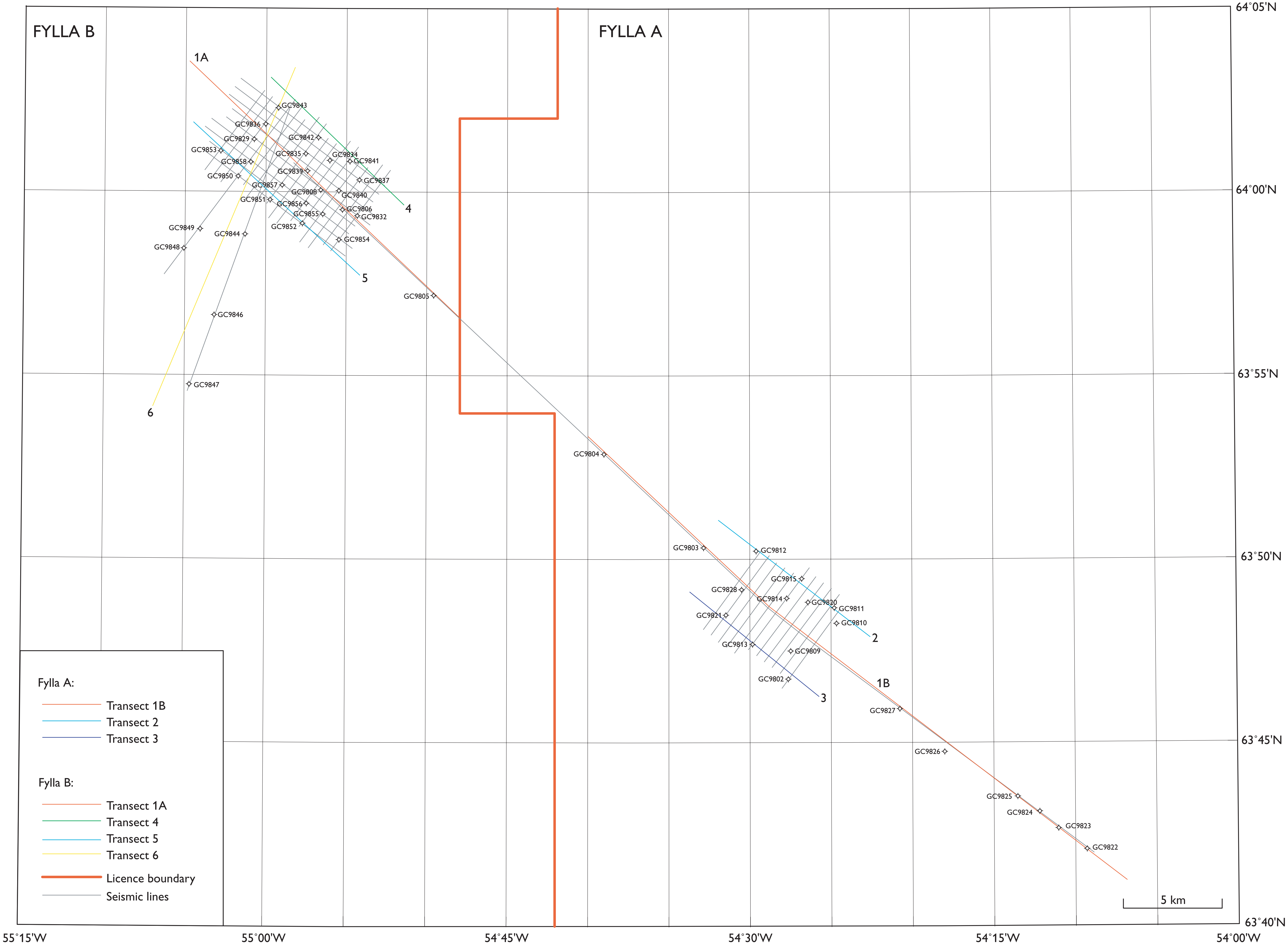

Fig. 2. Part of Fylla licence area with position of cores marked. Transect 1–6 are displayed at Figures 3–5.

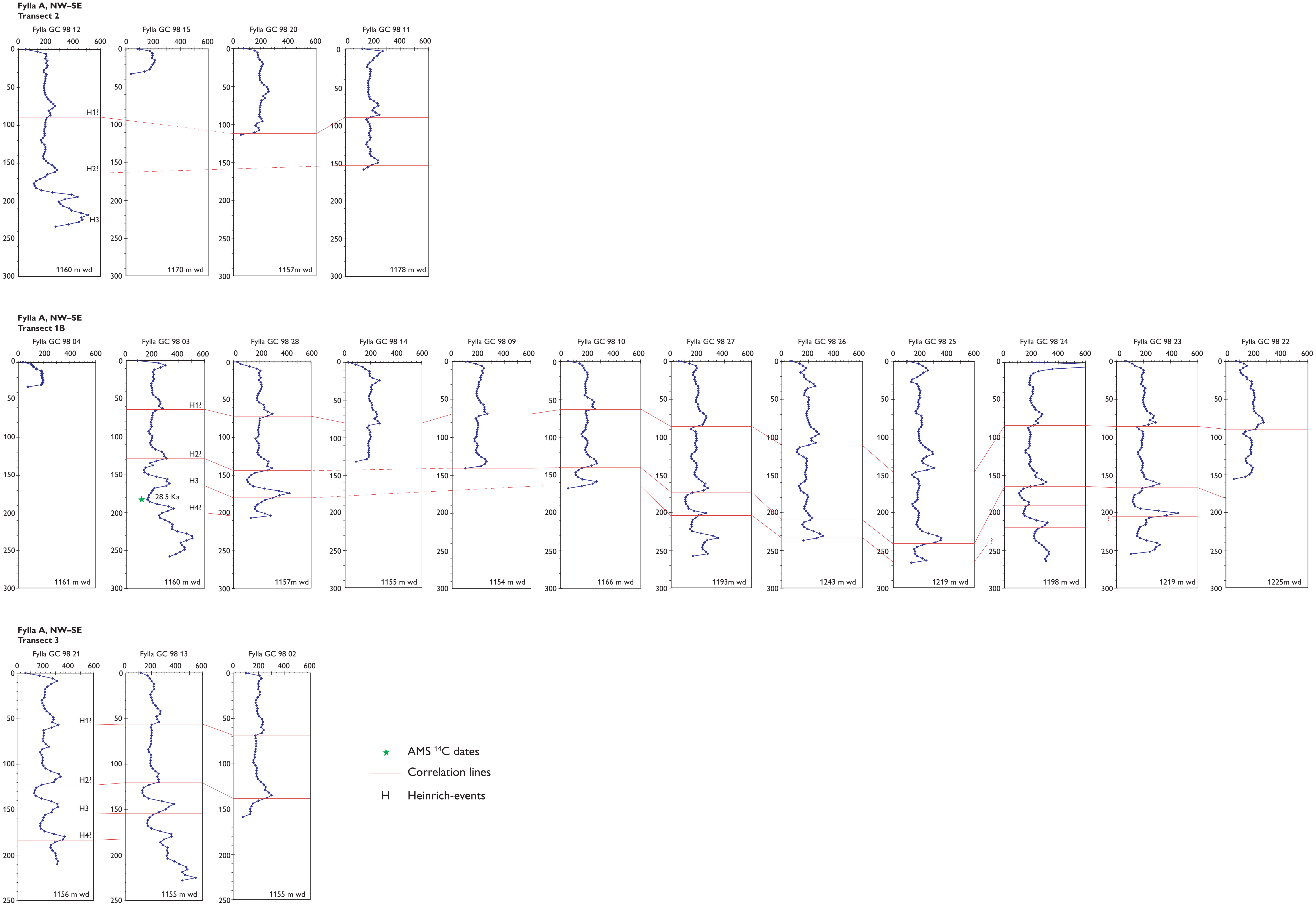

Fig. 3. Magnetic susceptibility profiles of cores from the Fylla B area (NW–SE).

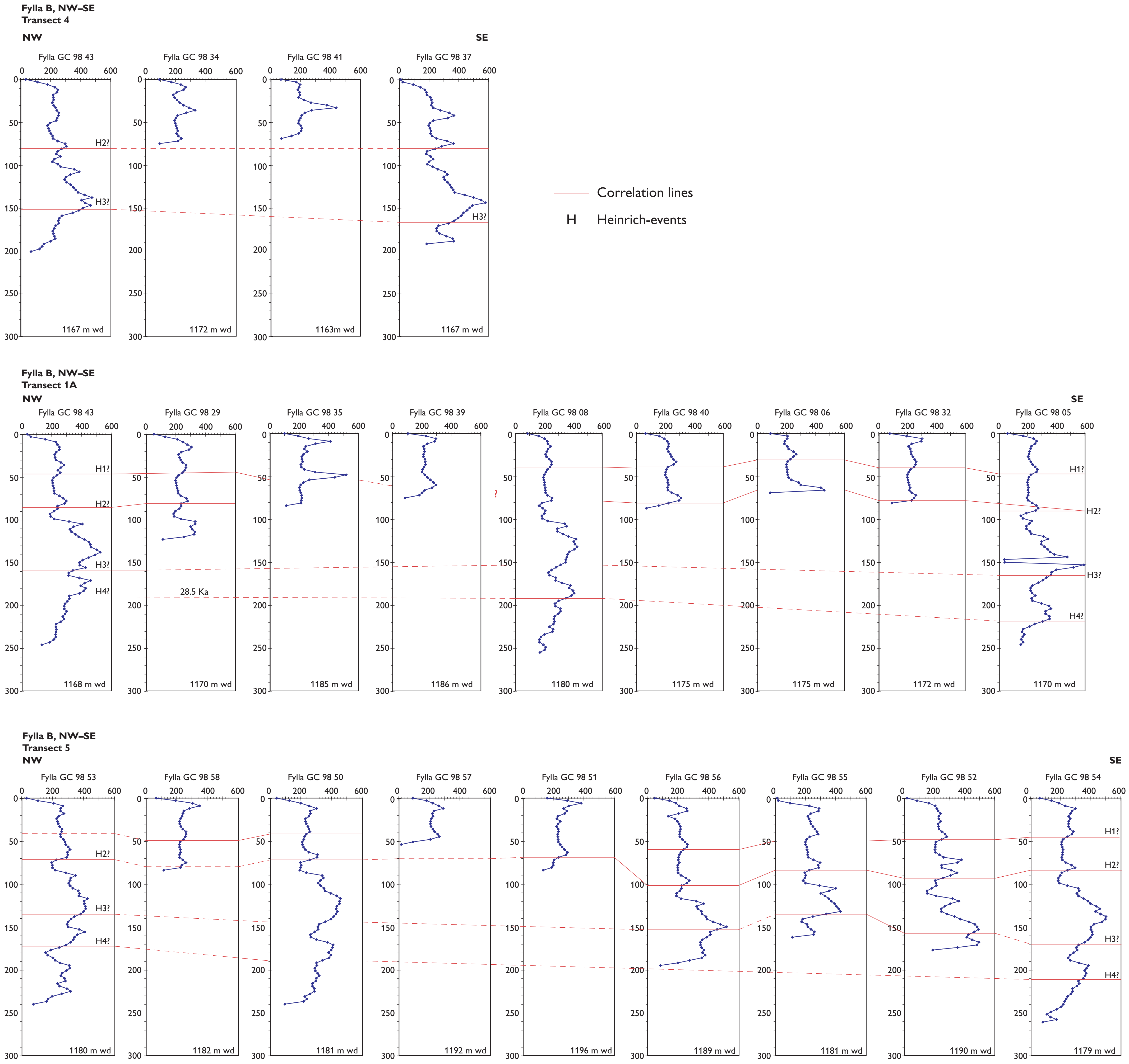

Fig. 4. Magnetic susceptibility profiles of cores from the Fylla B area (NW–SE).

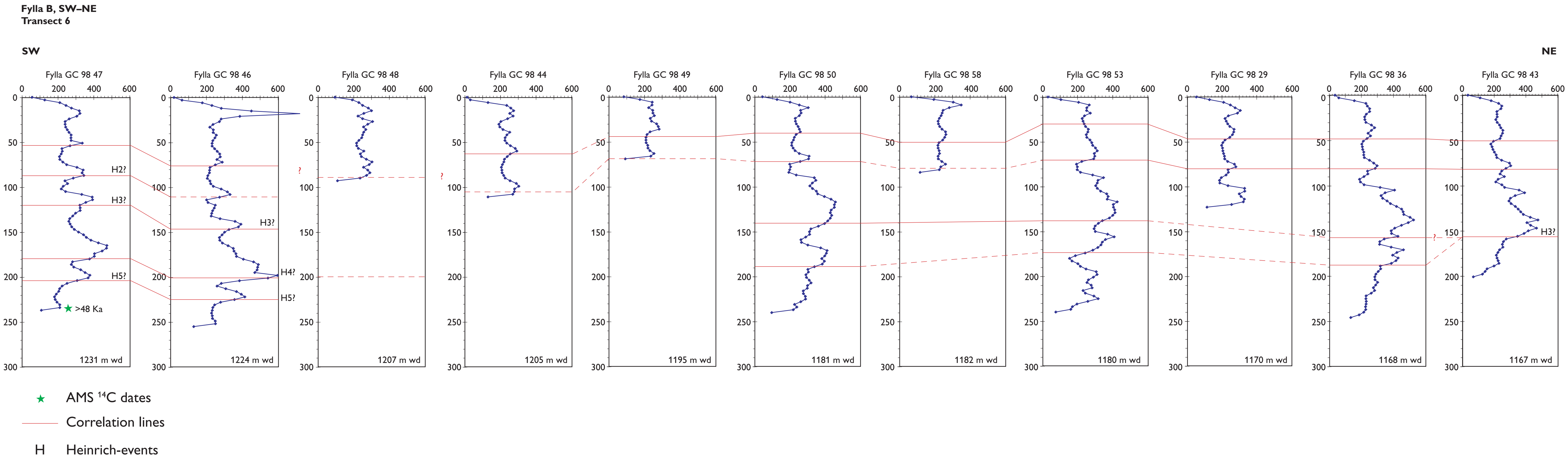

Fig. 5. Magnetic susceptibility profiles of cores from the Fylla B area (SW–NE).

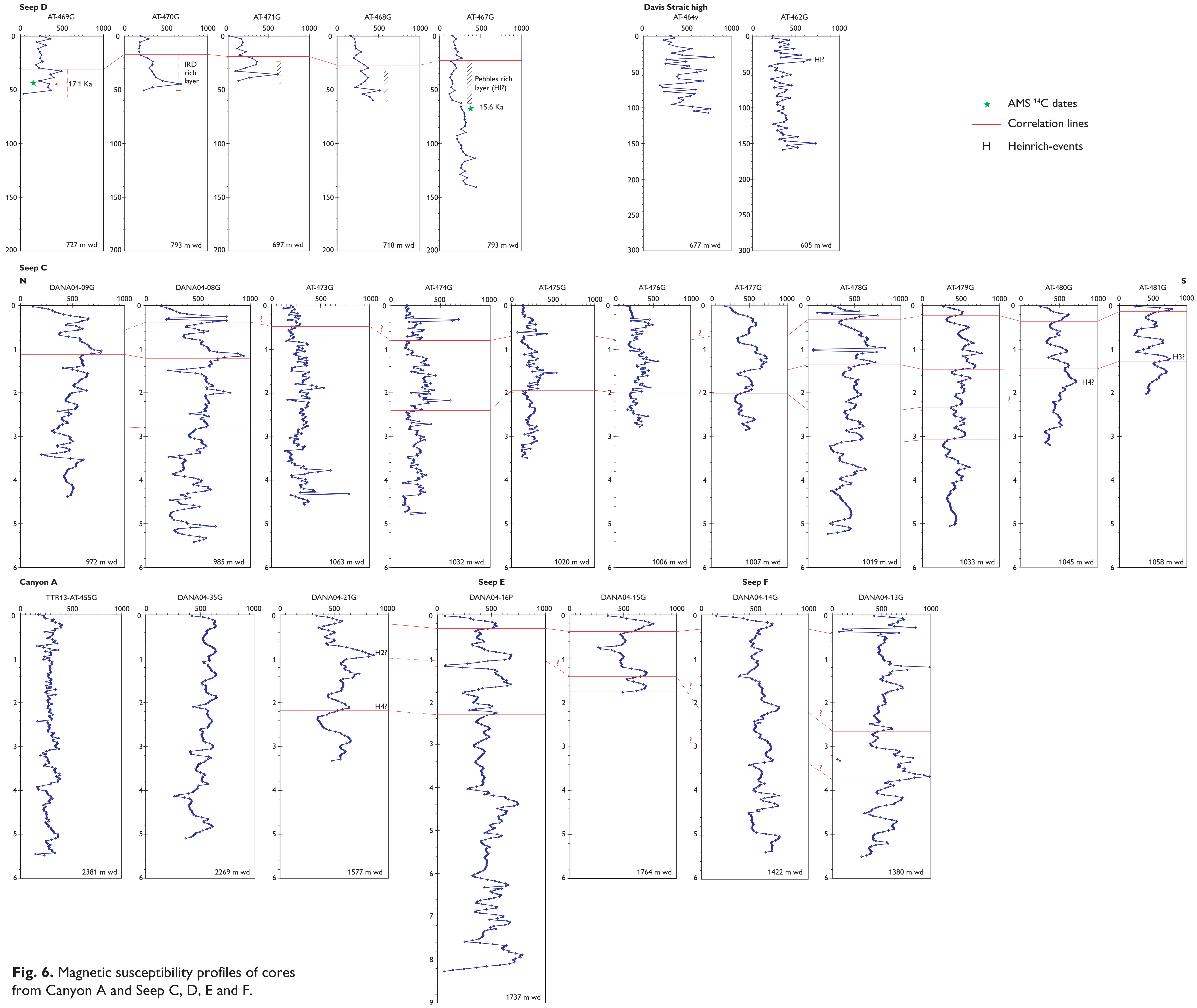

Fig. 6. Magnetic susceptibility profiles of cores from Canyon A and Seep C, D, E and F.