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3D seismic analysis of the Terschelling Basin Sliding Complex

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1 Introduction

Submarine landslides are a very important mechanism in moving big amounts of sediment down-slope. Gaining knowledge in these mechanisms can be very useful for understanding margin evolution. It is also known that slide deposits can act as sealing rocks for important reservoir units (for example the Omen Lange gas field that is located inside the headwall of the giant Storegga Slide). Moreover, submarine failures can generate large tsunamis causing destruction of coastal areas, for this reason they are considered a natural hazard.

Many Pleistocene/Holocene slope failures have been well described in the North Sea, most of them seem to occur in its northern sector (Hjelstuen, 2002; Laberg and Vollen, 2000; Solheima et al., 2005; Vanneste et al., 2006 and Bull et al., 2009a). This project focuses on mapping a Cenozoic slope failure in the Dutch sector of the North Sea Basin named the Terschelling Basin Sliding Complex. The term slide is used in its general meaning and should not be taken to imply a dominant slope failure mechanism, besides this, the terminology used in this report is after Frey-Martinez et al. (2006) and Bull et al. (2009b). The slides mapped for this study document that slope failure is instead a major process that governed the morphology of the southern North Sea region at least since Pliocene times.

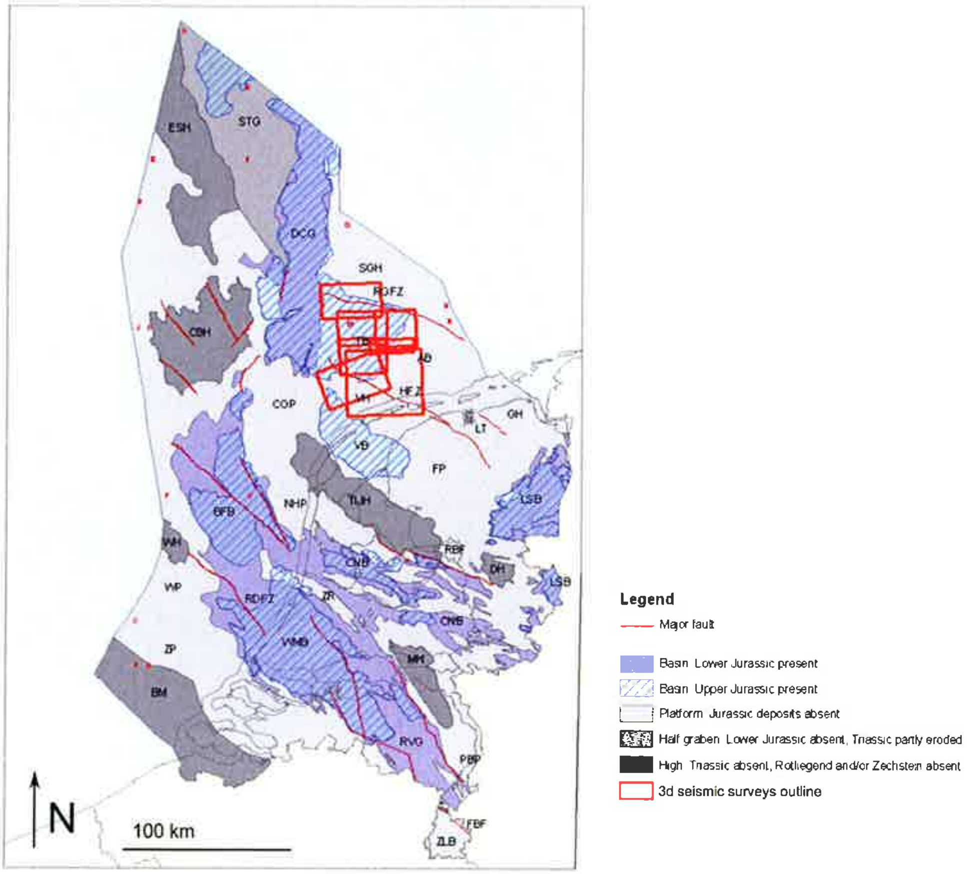


Figure 1: Mesozoic structural element map showing in red the location of the 3D surveys used for this study.

2 Geological Setting

This study focuses on the eastern part of the Dutch sector of the North Sea. The main structural elements present in the area are the Terschelling Basin (TB) and the adjacent highs: Schill Grund High (SGH), Ameland Block (AB) and Vlieland High (VH) which are all of Mesozoic origin (Fig. 1).
Mesozoic basinal structures formed during the break up of the Southern Permian Basin during several Late Jurassic-Early Cretaceous extensional tectonic phases associated with a major extensional event in the central and northern North Sea, and to the Arctic-North Atlantic initiation of sea-floor spreading (Late Kimmerian rifting phase). During this time rapidly subsiding basins formed while the adjacent platforms and highs underwent uplift and erosion.

The northern and southern boundaries of the Terschelling Basin correspond to important WNW-ESE oriented faults zones (Rifgronden and Hantum fault zones, RGFZ and HFZ in Fig.1) that were already active during the Late Carboniferous and were further reactivated during subsequent tectonic phases. The eastern and western boundaries show a NNE-SSW trend which correspond to the main salt structures in the area. Halokinesis in the Terschelling Basin started in the Early and Middle Triassic; subsequent important phases of salt movement occurred during Late Jurassic-Cretaceous rifting and during Late Cretaceous inversion phase. Salt structures remain active until present day, thereby disrupting the lateral continuity of Triassic to Tertiary sequences.

In the Cenozoic the entire North Sea region is characterized by thermal subsidence interrupted by Early Tertiary inversion of the Terschelling Basin and some halokinetic faulting (Ziegler, 1990). The upper Paleocene to middle Miocene succession is characterized by the deposition of pelagic and hemi-pelagic mudstones in a distal setting. This succession, which is approximately 500 m in thickness in the Terschelling Basin, is deformed by polygonal faulting caused by volumetric contraction of the (Cartwright, 1994). The upper Paleocene to middle Miocene succession is separated from the Late Cenozoic succession by a major unconformity, called the Mid-Miocene Unconformity (MMU; defined by Michelsen et al. (1998)). The mechanism that caused the formation of the unconformity is still debated today. Most authors suggest that it represents a transgressional surface (corresponding to the so-called Hodde transgression) that is characterized by sediment starvation and/or condensation (Huuse & Clausen, 2001; Gemmer et al., 2002). Post Mid-Miocene sedimentation is dominated by the progradation of an enormous fluvio-deltaic system. During the early stages of this delta system (Late Oligocene) the input direction was from the north-east. In this period most sediments were delivered in the basin by rivers draining the Fennoscandian shield. In later stages the input direction moved clockwise from north-east to purely east and than to south-east when the Rhine-Meuse river system merged with the Baltic system in Late Pliocene (Huuse et al., 2001; Kaulmann 2004; Kaulmann et al., 2006; Kaulmann & Wong 2008).

3 Dataset and Methodology

3.1 Data

A set of seven 3D multichannel seismic reflection surveys is the primary source for this study (the exact location of the surveys is shown in figure 1.). These data have become publicly available and were provided by TNO B&O. The line spacing is 25 m for both in-lines and cross-lines. A standard seismic data processing sequence was applied to the data including a 2-D by 2-D post-stack time migration. The Cenozoic interval, which is the object of the study, has a time-thickness of about 900 ms. The surveys have been interpreted using Petrel software.

The studied succession shows a very homogeneous layering of sediments in well logs, of which only the GR was available. Since there was no clear distinction between disturbed and undisturbed sediments to be seen in the GR, it was decided not to elaborate on well logs in this study.

3.2 Methods

The sliding complex is defined on 3D seismic data by the mapping of the two reflectors constituting the lower and upper boundary of each single sliding body. In addition other reference horizons have been mapped. All these horizons have been mapped manually every 10 in/cross-lines. The top surface is usually not represented by a single reflector but rather the boundary between a disturbed and chaotic seismic facies and the overlying undisturbed strata. Seismic volume attributes extraction like amplitude and variance and the construction of time slices where used to help the interpretation. Following the interpretation horizons have been converted into surfaces to be able to calculate thicknesses and volumes. Time-depth conversion is done using an average velocity 2 km/s.

3.2.1 *Slide identification criteria*

The Cenozoic sedimentary succession of the Terschelling Basin area consists of three main seismic facies units: (1) plain stratified, (2) clino-stratified and (3) massive chaotic (Fig. 2 and 3). The plain stratified units represent distal marine sedimentation. The clino-stratified units correspond to the prograding delta slope. The massive chaotic facies was interpreted to correspond to submarine slope failure deposits. This interpretation is mainly based on two criteria: the planview geometry observed in variance time slices, and the presence of characteristic features recognized in the seismic. These features comprise: (1) the existence of a headscarp, that can be easily recognized in seismic sections as a steep ramp that laterally separates the chaotic seismic facies from the upslope undisturbed sediments that still preserve the pre-failure stratigraphy; (2) the alignment of rotated faults blocks close to the headscarp; (3) the presence of translated intact blocks within the slide deposit; (4) the presence of ramps and flats in the basal shear surface, the gliding planes in fact often seem to jump between different stratigraphic levels; (5) the presence of thrust systems and pressure ridges in the toe region and (6) the existence of a runout region (Fig. 2). Many of these additional features can also be used as kinematic indicators (Bull et al., 2009b) and so helped in reconstructing the direction of flow.

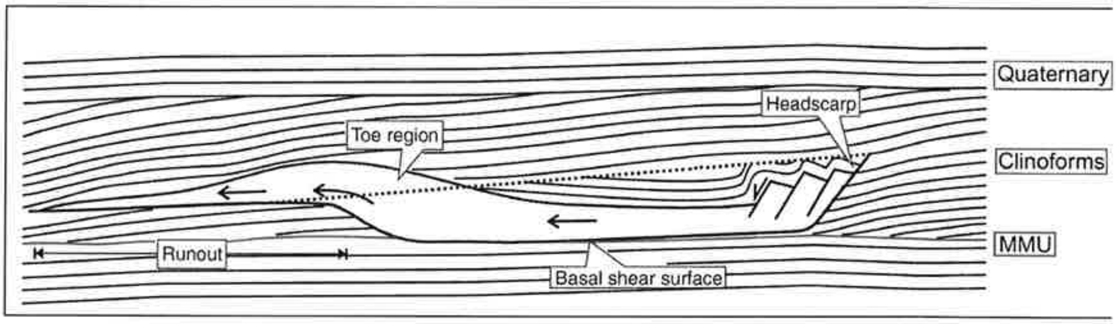
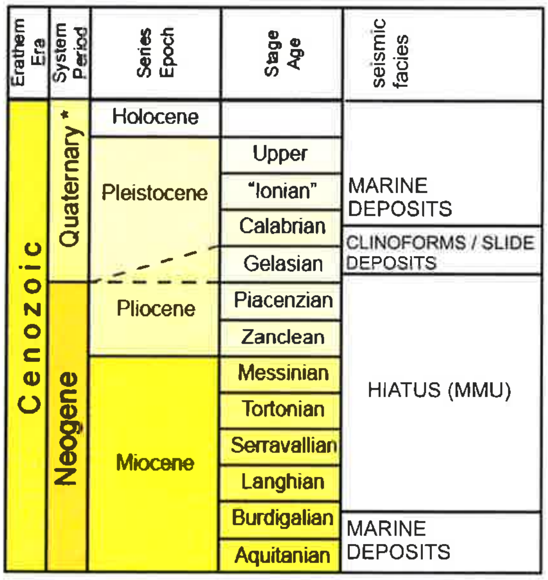


Figure 2: Schematic sketch of a frontally emergent slide (modified from Frey-Martinez et al., 2006).

4 Results

4.1 Age of the studied sediments

In order to understand the age of the sliding complex cuttings coming from well G16-06 and M07-01 have been analysed (see Fig. 4 for exact location). The results show that the deposits on top of the MMU in the G16 block are Zanclean in age, and those from the M07 block are instead Gelasian in age (Fig. 3). This result is in agreement with the expected progradation trend of the delta system. Sediments right below the MMU have been assigned to Burdigalian in both samples. This implies that the MMU represents a hiatus of up to 18 My (Fig. 3). In well G16-06 Gelasian deposits have a thickness of about 200 m, this leads to an average sedimentation rate of about 30 cm/ky.



Erathem Era	System Period	Series Epoch	Stage Age	seismic facies
Cenozoic	Quaternary *	Holocene		MARINE DEPOSITS
		Pleistocene	Upper	
			"Ionian"	
			Calabrian	
			Gelasian	CLINOFORMS / SLIDE DEPOSITS
	Neogene	Pliocene	Piacenzian	HIATUS (MMU)
			Zanclean	
		Miocene	Messinian	
			Tortonian	
			Serravallian	
			Langhian	
			Burdigalian	MARINE DEPOSITS
			Aquitanian	

Figure 3: Age and facies of the interpreted sequences in offshore block M07. The stratigraphic chart is adapted from ISC (2009).

4.2 The Terschelling Basin Sliding Complex

Six slides have been mapped in the study area. Each single slide has been named after its position on the North Sea blocks and is labeled in figure 4. It is possible to see the entire body of five out of the six mapped slides. SG16 instead is only partly visible in the available 3D surveys. Headwalls and sidewalls are relatively clear, whereas the distal parts of the slides are much more difficult to distinguish in seismic sections. Therefore runout distances are not estimated. A brief schematic description of each single slide follows below.

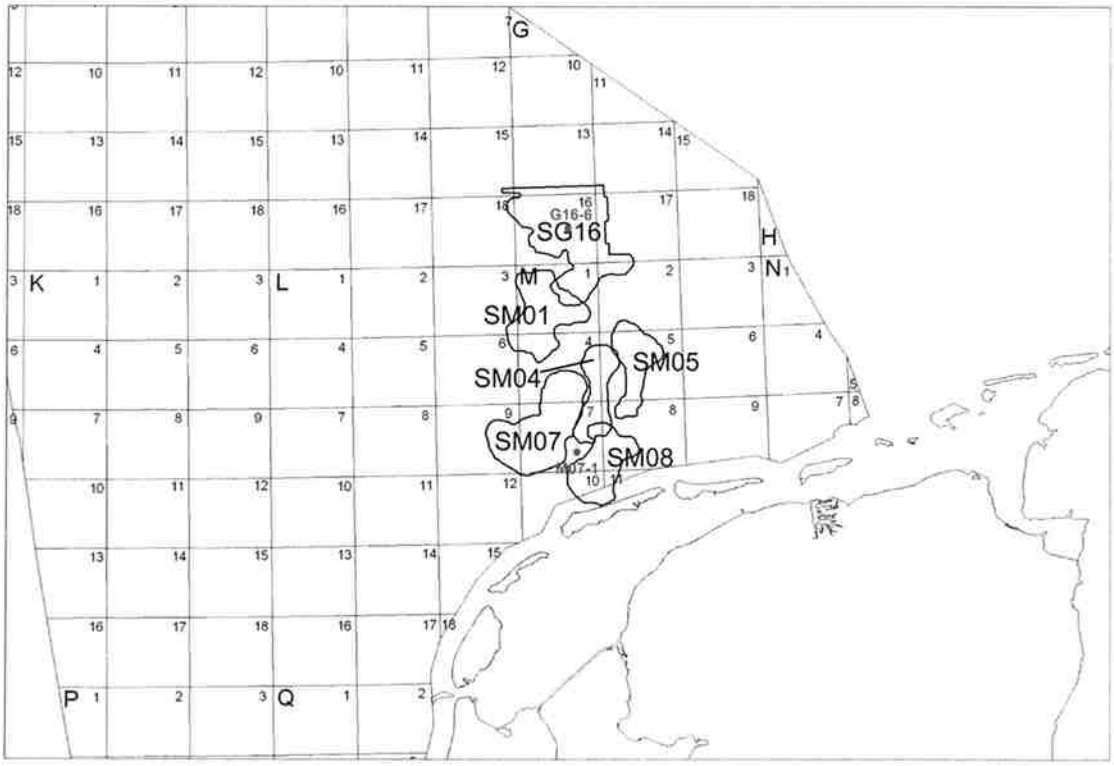


Figure 4: Outline of the six mapped sliding bodies and location of well G16-6 and M07-1

4.2.1 *SLIDE G16*

Only the toe region of this slide is visible in the available 3D seismic surveys. Therefore the volume is not calculated. However, from the dimension of the toe region it is likely that this is the biggest slide in the study area and that the head region may be located in the German or even in the Danish sector of the North Sea. The derived main direction of flow is south-west.

A very large runout zone is visible in the coherency time slices identified in seismic sections as a thin layer (10-50 m) of chaotic discontinuous reflectors (Fig. 5). This part of the slide seems to be constituted by more stacked debris lobes. In the interpreted time slice of figure 5. a lobe connected to the slide by a narrow channel is well imaged. In this area of the slide the grade of remoulding is extremely high.

A large accumulation zone is very well imaged in cross sections; here the slid sediment can reach thicknesses up to 350 meters and large compressional structures like thrust faults and folds are well imaged in seismic sections (Fig. 6). The basal shear surface (BSS) corresponds to the MMU for most of the visible part of the slide; however it frequently jumps to deeper or shallower levels.

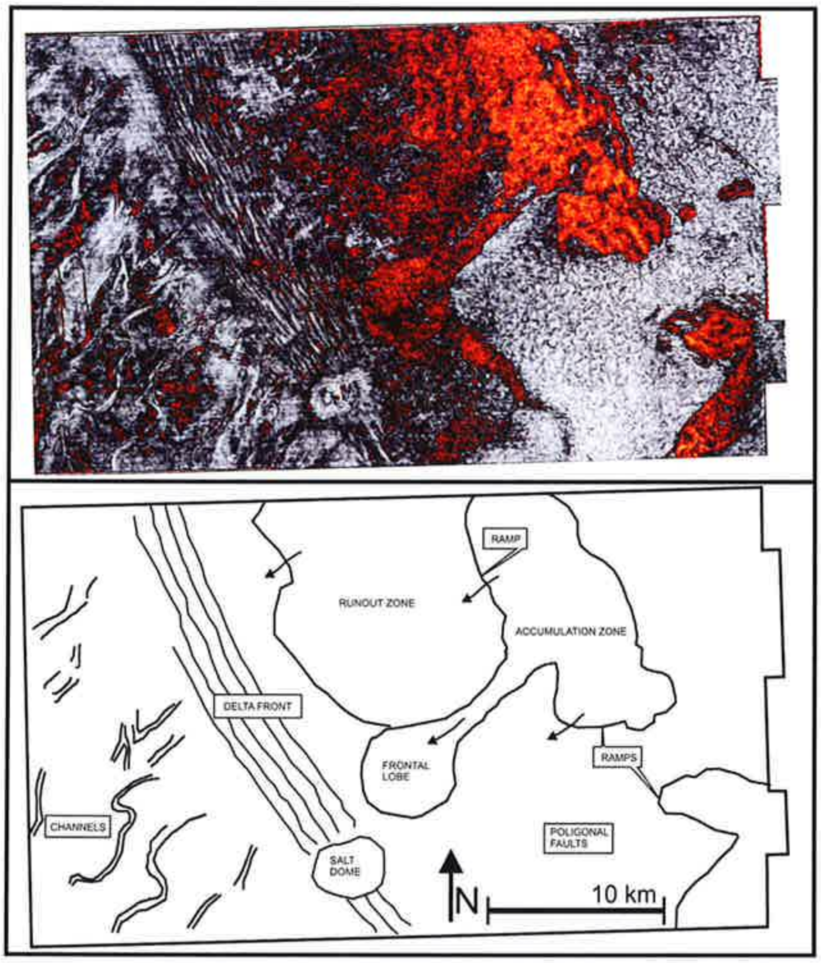


Figure 5: Variance time slice from block G16 at -820 ms TWT and interpretation showing the toe region of SG16

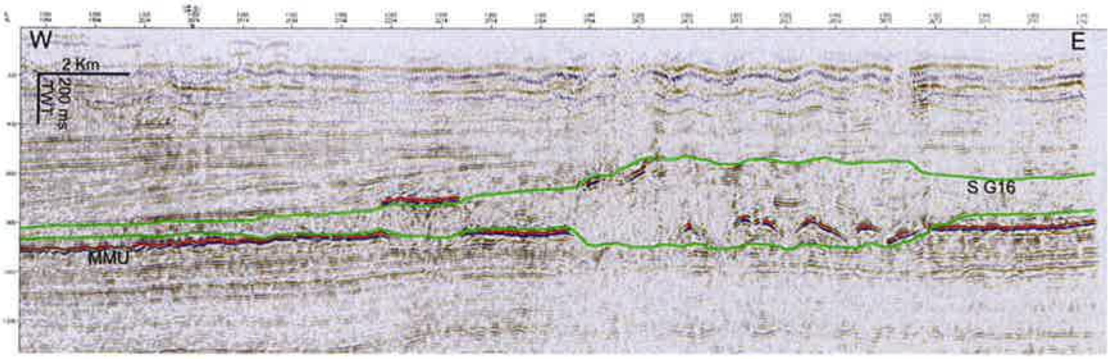


Figure 6: Interpreted inline 1355 from G16 block showing the toe region of SG16. The location of the section is shown in Fig. 5

4.2.2 *SLIDE M01*

SM01 covers a total area of 300 km2 and moved 3.4 km3 of sediment. However this number represents a minimum estimated volume because runout deposits are very uncertain and therefore have been only partially mapped. The slide is almost entirely located in block M01 but some runout deposit can reach the M04 block. The direction of flow is south for the western part and west-south-west for the eastern part. SM01 is somehow anomalous relative to the other mapped slides. The biggest difference is in the BSS which correspond to a clinoform in the head domain; only in the toe domain it ramps down to the MMU (Fig. 8).

Two separated headwalls are present (Fig. 7) suggesting that SM01 is made up by at least two different events, seismic data however do not allow distinguishing between the two different bodies. Therefore SM01 is treated as a single slide. Only few coherent tilted blocks are visible in the western head region, besides that SM01 seems to be constituted by material much less coherent than the other mapped slides where many more coherent tilted blocks occur. This suggests that SM01 was triggered much faster after the sedimentation of delta deposits than the others; there was less time available for cementation

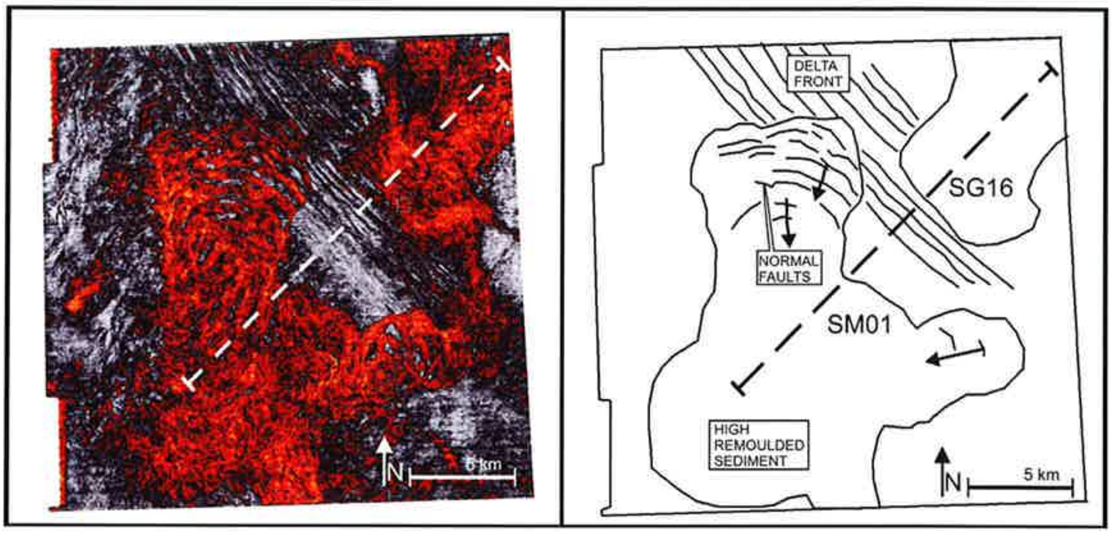


Figure 7: Variance time slice from block M01 at -760 ms TWT and interpretation showing SM01 and SG16

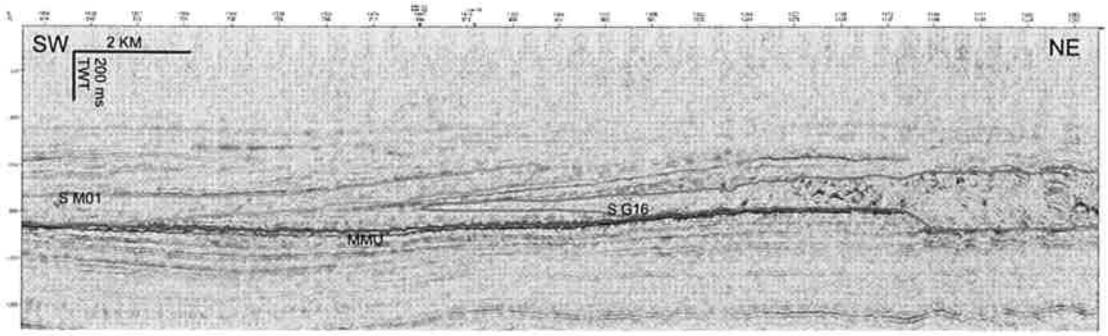


Figure 8: Interpreted random line from block M01 showing SM01 and SG16. The location of the section is shown in Fig. 7

4.2.3 SLIDES M04 and M05

These two slides have been mapped separately, but they will be described together because they show many similar features. They cover an area of respectively 180 km2 and 190 km2, and mobilized 2.9 km3 and 2.8 km3 of sediment. The two sliding bodies are separated in the translational domain by a large salt dome in between them. This complicates the interpretation because a disturbed zone related to the salt dome interferes with the slides. The slides present two different distinct headwalls. However an external disturbed halo all around the head region is visible outside the main sliding bodies. Large coherent blocks tilted by normal listric faults are present in the head domains (Fig.10). The main direction of flow is purely southwards for both slides. This is in agreement with the orientation of faulting in the head region of SM04 but is not with the one of SM05 that is instead pointing more south-westwards (Fig. 9). Thrust structures are visible in the translational domain of SM04. SM05 is characterized by a particular low degree of remoulding that seems to diminish more and more away from the headwall. This trend is anomalous compared to the other mapped slides where the degree of remoulding is instead increasing toe-wards. The disturbed zone of SM04 in the toe region is mixing up with other sliding bodies (SM07 and SM08) that are probably cutting it. A distinct runout region is not visible and this suggests that SM04 and SM05 may be the only frontally confined mapped slides in this region; all the others in fact are frontally emergent.

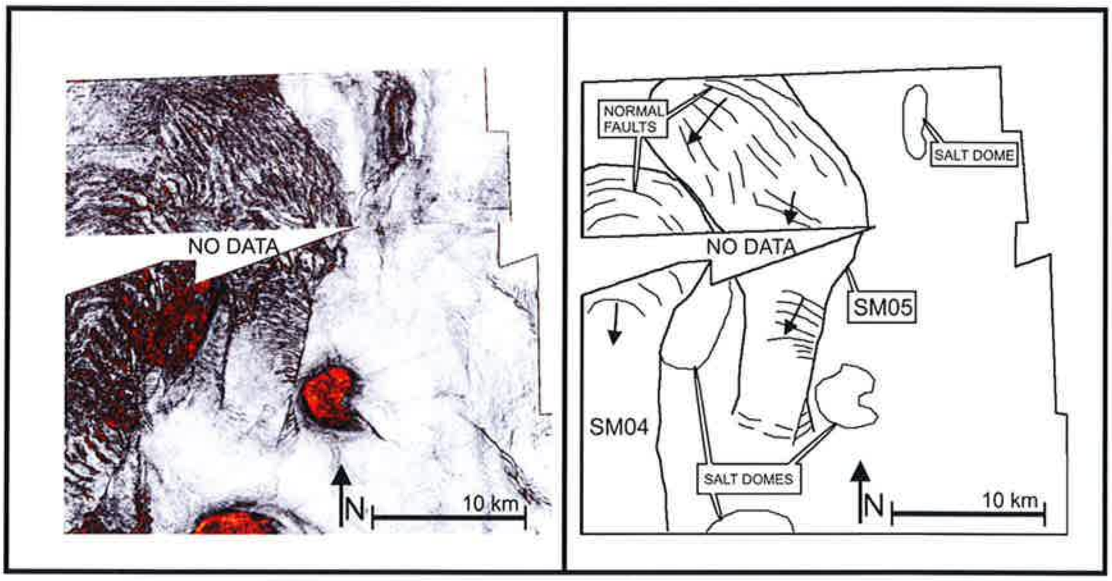


Figure 9: Variance time slice from blocks M05-M08 at -660 ms TWT and interpretation showing SM04 and SM05

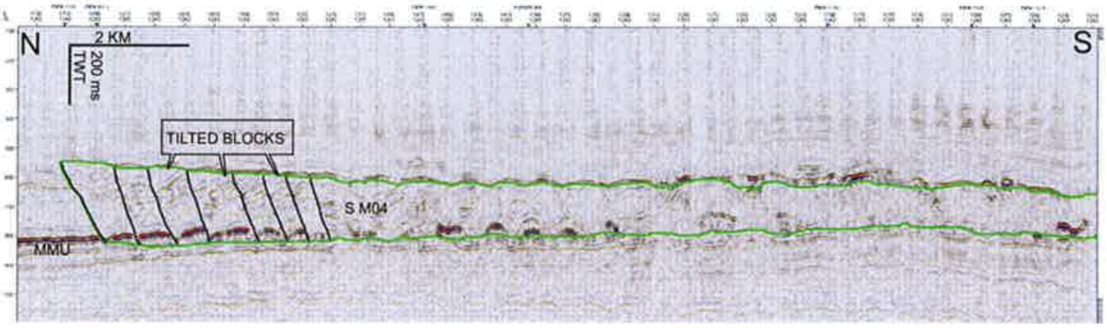


Figure 10: Interpreted crossline 1192 from M04 block showing SM04. The location of the section is shown in Fig. 11

4.2.4 *SLIDE M07*

This slide covers a total area of 410 km2 with a total volume of 4.6 km3. The main body and the toe region are located in the M07 block, the headwall is present and well imaged in the M04 block. The main direction of flow is initially purely southwards. It deviates to south-west in the distal part probably due to local topography. Large coherent blocks tilted by normal listric faults are present in the head region and through the first half of the sliding body. Buried undisturbed sediment blocks are also present (Fig. 11). These may represent either translated blocks that slid on the BSS without being remoulded or remnant blocks that did not move at all. The seismic data do not allow a differentiation between these processes.

Hardly any depletion is visible in this region, so toe-wards thickening is not observed. As a basal shear surface SM07 mostly uses the MMU, however a short ramp (10-20 m high) separates the runout region from the core of the slide. Long continuous pressure ridges are very well visible in variance time slices of this region (Fig. 11).

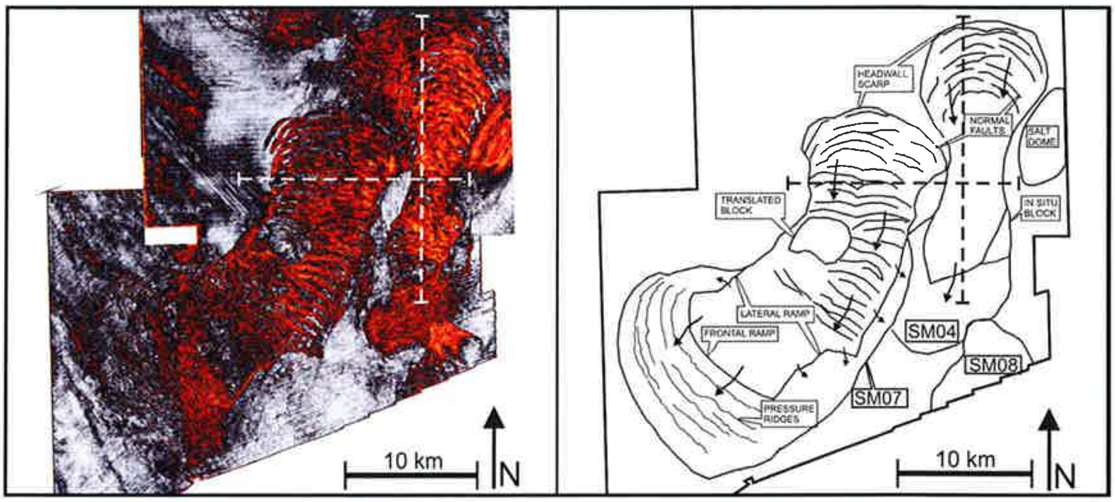


Figure 11: Variance time slice from blocks M04-M07 at -760 ms TWT and interpretation showing SM04 and SM07 and a small part of SM08

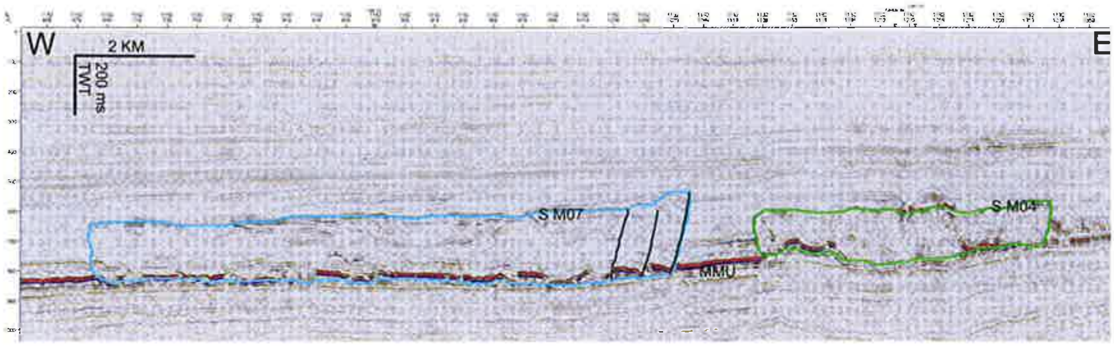


Figure 12: Interpreted inline 1192 from M04 block showing SM04 and SM05. The location of the section is shown in Fig. 11

4.2.5 *SLIDE M08*

This slide covers a total area of 230 km2 for a total volume of 1.7 km3 of sediment mobilized and is located on the southern part of the M08 block. The main direction of flow is south-westwards.

The head region shows one big upslope step suggesting a retrogressive development, which means that the failures were initiated on the lower slope and propagated upslope. Remnant blocks are visible in this region, in seismic sections it is possible to observe a diminishing trend in spacing and dimension of the blocks basin-wards (Fig. 14). Between the toe region and the translational domain a large area of totally undisturbed reflectors is visible. This zone is located at the transition between the compressional and the extensional regimes, and it may represent the scar of a totally evacuated area (Figs 13 &14). The MMU is again the principal gliding surface, however sometimes the BSS ramps down to lower stratigraphic levels.

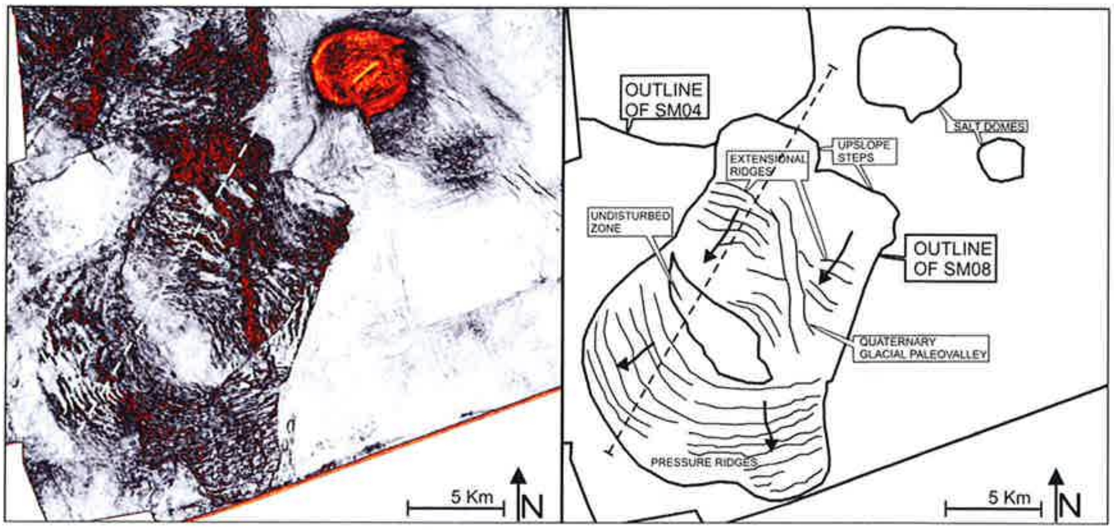


Figure 13: Variance time slice from block M08 at -680 ms TWT and interpretation showing SM01 and SM08 and a small part of SM04

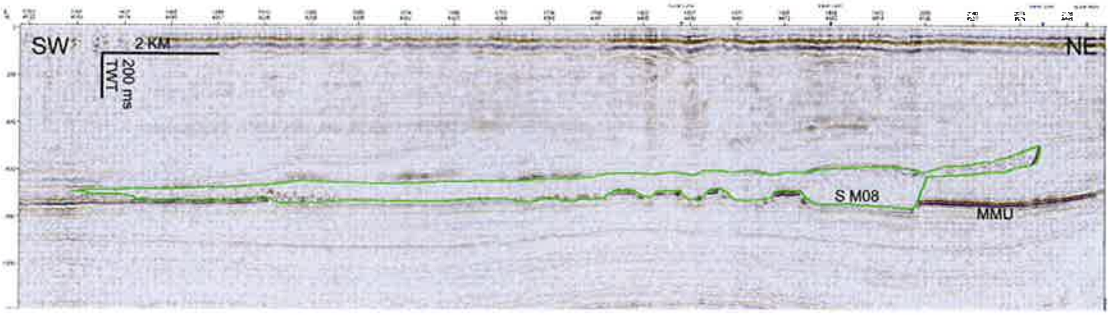


Figure 14: Interpreted Random line from M08 block showing SM08. The location of the section is shown in Fig. 13

4.3 The delta system

The Cenozoic sediments of the study area were deposited by the huge Eridanos delta system. According to the literature the prograding system developed from the north-east since Late Oligocene times and has been active until the Late Pliocene when it merged with the Rhine-Meuse system draining from south-east. Age determinations of the MMU in the Norwegian, Danish and German sector of the North Sea are confirming this regional progradation trend (Huuse et al., 2001). In order to understand the local trend of progradation of the delta some clinoforms have been mapped. The result is roughly concordant with the regional trend previously described (Ziegler, 1990; Kuhlmann, 2004).

Two different directions of progradation have been found to be active at the time the sliding complex formed (Fig. 15); one with an input from north-east, the other one from east. The latter seems to be older; the sequences from the north-east are overlying those coming from the east. However, it is possible that the two systems were actually active at the same time. Probably most of the sediment is delivered in the basin by many ice streams draining glacial erosional products from the FennoScandian ice sheet during deglaciation or early interglacial times.

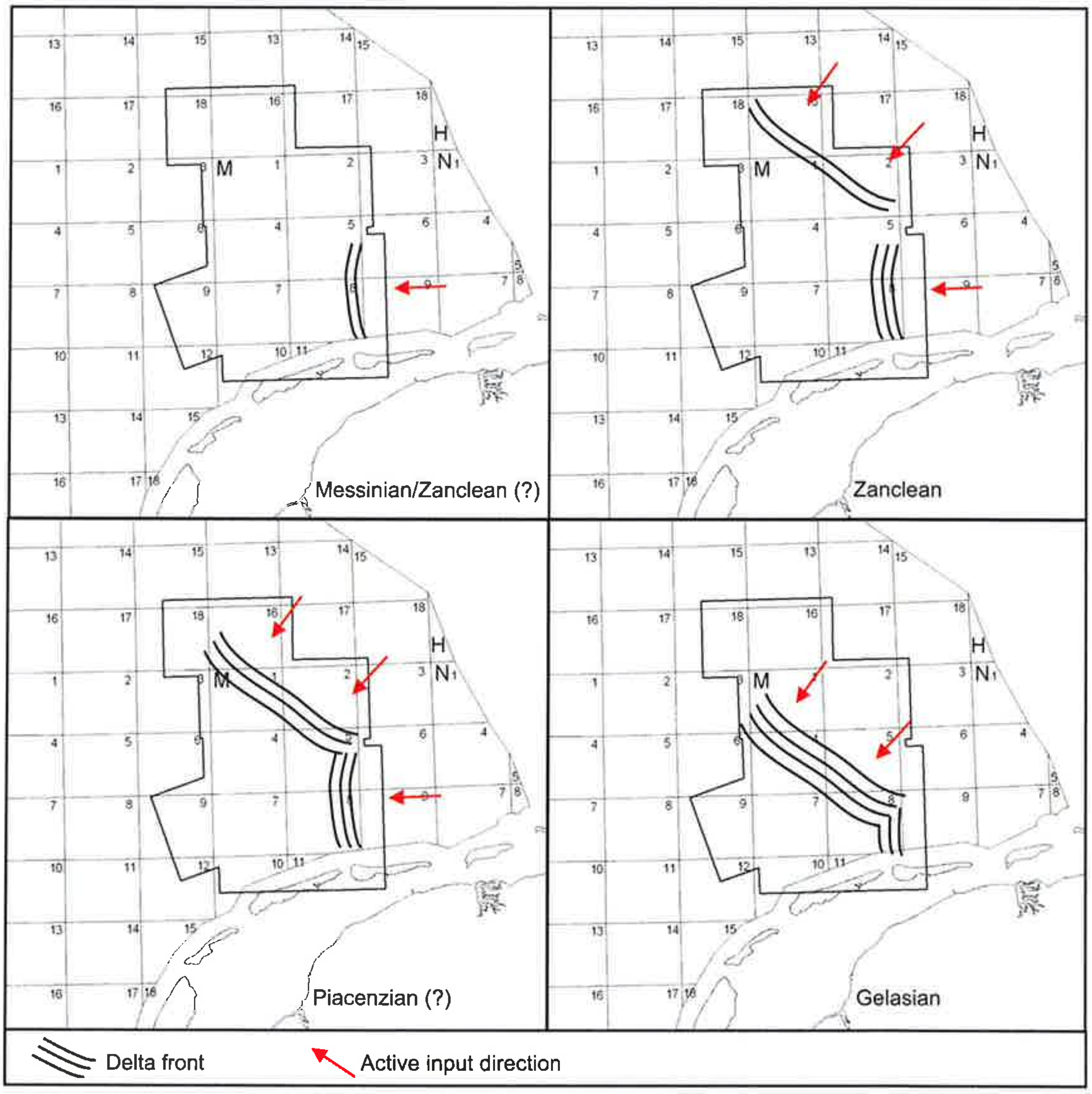


Figure 15: Reconstruction of the delta progradation in the study area from Messinian to Gelasian

5 Discussion

5.1 Direction

In submarine slope failures the direction of flow is entirely controlled by the pre-existing topography. The gross transport direction in the mapped slides has been derived both from the interpretation of variance time slices and from the presence of kinematic indicators. For most of the slides the direction is south-west (Fig. 16), which is in accordance with the assumed strike of the slope derived from the assumed setting of the delta system. However, SM04, SM05 and SM07 present a different picture. SM07 has an initial southward direction of flow that rotates to south-west only in the toe domain (Fig. 16). SM04 has a pure southwards direction. SM05 also presents a pure southward direction of flow but the normal faults in his head region are dipping south-west (Fig. 9). All these features suggest that the slope topography was not constant over time. The presence of delta sequences with two different input directions is probably one of the reasons for this irregularity. The presence of active salt tectonics may also affect the topography. At least six salt domes have been found to disrupt the MMU at present day (Fig. 17). The thickness of the salt structures in Gelasian ahs been calculated. The result is that salt domes where creating a small bump (10-20 m) in the MMU in that period which was probably enough to deviate the sliding sediment.

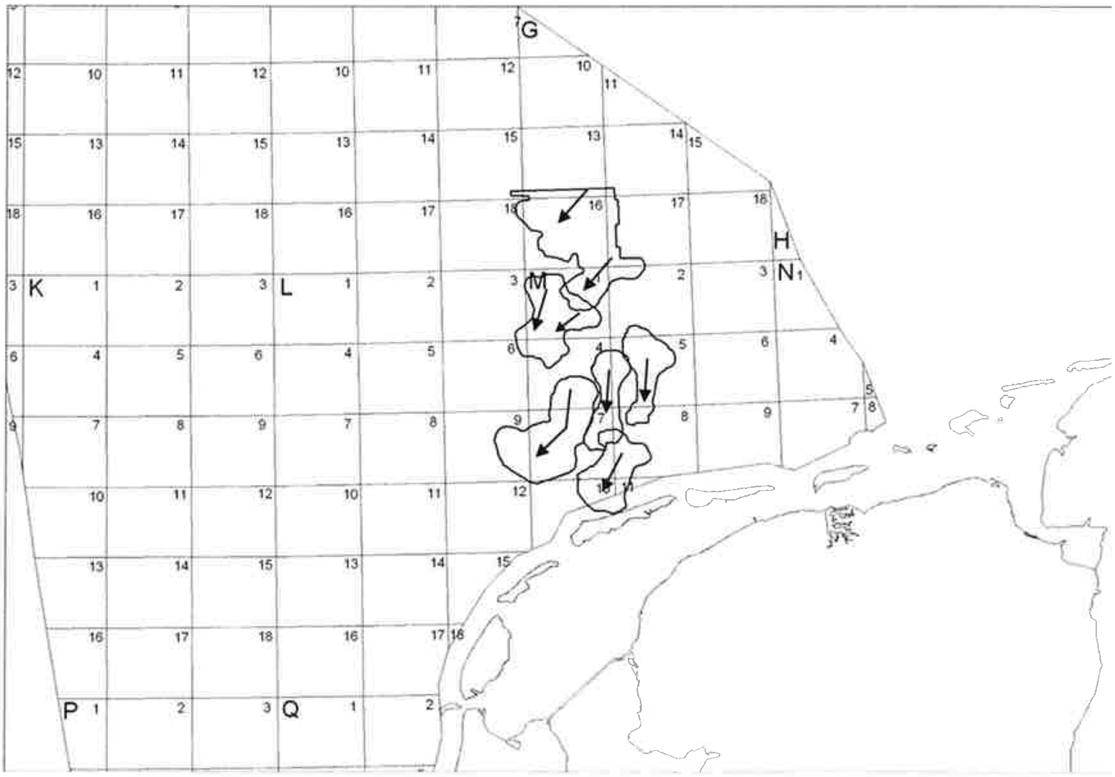


Figure 16: reconstruction of the gross direction of flow in the six sliding bodies

5.2 Chronology

Although a high resolution chronology can not be established due to the limited amount of biostratigraphical data, it is reasonable to assume that the sliding events followed a north east-south west trend, indicating SG16 as the oldest slide and SM08 as the youngest. This is according with the direction of the slides and the progradation trend of the delta system.

5.3 Triggers

The triggers for submarine slope failures to occur can be many. They are difficult to prove and usually a combination of processes is involved. It is known that the movement is initiated when the downslope-oriented shear stress exceeds the shear strength (resisting stress) of the slope sediments. To reach this condition it is assumed that it is necessary to have a prerequisite that causes instability in the slope and an external trigger that causes the slope to fail (Hampton et al., 1996). The most common prerequisite proposed for high latitude-failures is glacial-interglacial variability in sedimentation rates because it creates different grades of consolidation in the succession leading to instability (Hjelstuen, 2002; Laberg and Vollen, 2000; Vanneste et al., 2006; Bull et al., 2009a). High sedimentation rates are also often proposed because rapid loading is supposed to create an excess in pore pressure that reduces the effective geomechanical strength of the slope causing potential instability (Solheima et al., 2005).

Both prerequisites seem to be present in the Terschelling Basin area. Moreover, the presence of two active delta sequences with different input directions can also cause instability of the slope. Still an external trigger is supposed to be necessary to cause the slope to fail. Although the southern North Sea Basin is considered to be largely aseismic at present day, salt tectonics related seismicity is a prime candidate as a potential trigger for the Terschelling Basin Sliding Complex. figure 15 shows that both salt domes and faults occur in the area of the sliding complex. Individual Earthquakes were probably too small to actually cause the slope failure. However, it is known that the accumulated strength reduction following several small earthquakes can be an effective trigger mechanism (O'Leary, 1991). With present day data however is not possible to provide any actual clue for these hypotheses.

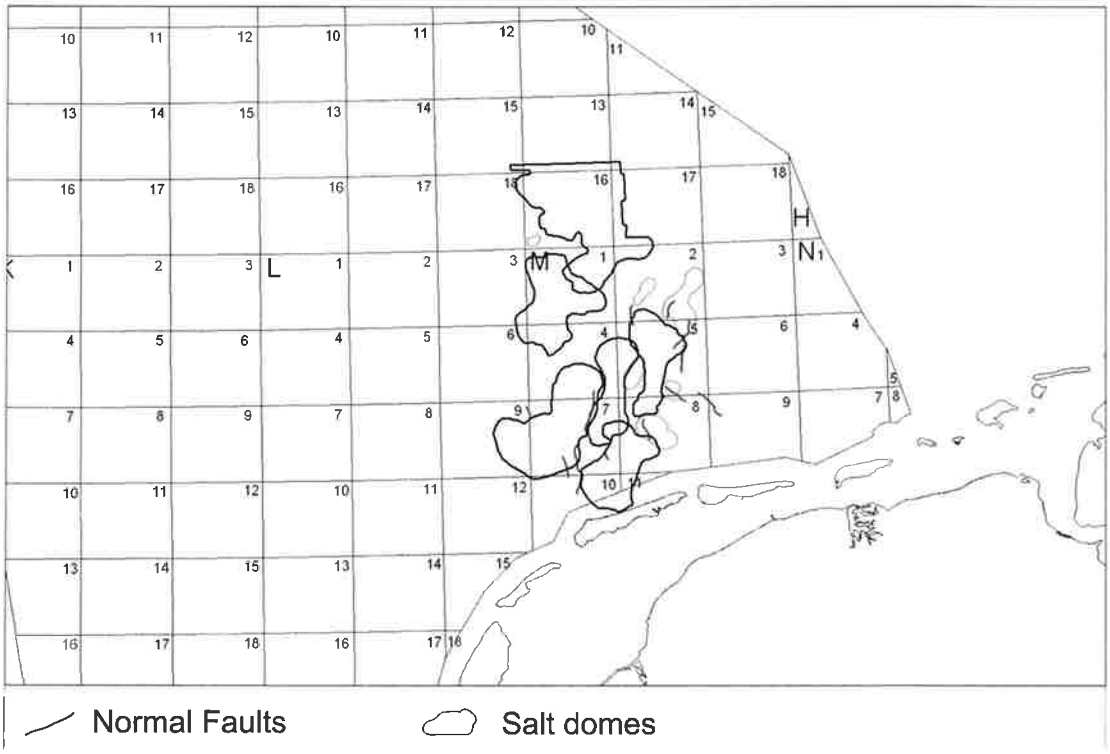


Figure 17: Location of major faults and active salt domes

6 Conclusions

The following main conclusions can be summarized from this study:
Six sliding bodies were found to be present and were mapped in the Terschelling Basin area within the Pliocene-Pleistocene sedimentary succession.
The main transport direction of the slides has been derived to be mostly south-westwards.
The slides located in the northern sector of the studied area are older than those located in the southern one.
Two different input directions were found to be active in the local development of the Eridanos Delta system, one coming from east, the other from north-east.
High sedimentation rates, high variability in the sedimentation regime in combination with salt tectonics related seismicity is proposed to explain the failure mechanism, causing the slides to occur.

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8 Signature

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