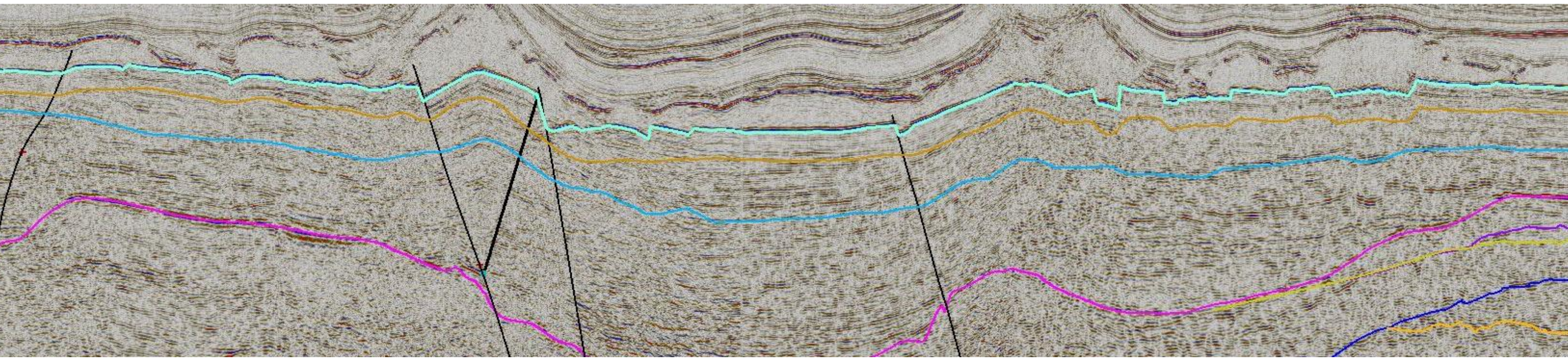
Dinantian carbonate development and related prospectivity of the onshore Northern Netherlands



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Contents

All chapters in this research report can be read separately.

Abstract

A petroleum system may be present in the Carboniferous Dinantian carbonates in the Northern onshore Netherlands. This play has been evaluated by using seismic, well data and analogues. Only 2 wells penetrate this succession in the study area: UHM-02 and LTG-01. The Dinantian carbonate buildups were encountered at depths of approximately 4000m and comprise a muddy fine-grained matrix with a low initial porosity. Carbonate production in the Dinantian consists mostly of microbial mats, which grow typically underneath upwelling zones at low latitudes near continental shelves where sea water temperatures are warm to moderate. The post-Caledonian extension phase created a horst and graben system, where carbonate build-ups developed on the highs. Basinal, deep water shales onlap these build-ups, potentially providing hydrocarbon charge. Seismic mapping resulted in the identification of 4 carbonate build-up structures. The build-ups in the Southwestern part of the study area had been uplifted, resulting in the tilting of a flat topped platform while faulting isolated a part of the build-up. The Northeastern build-ups developed on paleotopography which might have been formed by a Devonian reef. The Hantum fault zone and the Lauwerszee Trough separated the western carbonate build-ups from the ones in the East. The Hantum fault zone has a high geothermal gradient probably resulting in (over)maturation of shale deposits in the Lauwerszee Trough. Analogues show that reservoir quality improves at progradating slope deposits and Belgian outcrops suggest a highstand in Late Visean, which can be related to progradation. On seismic, progradational sequences can be recognized in the study area. Also fractures are believed to be more abundant at the slope, simultaneously improving reservoir quality and possibly posing a risk to seal capacity. Because of the deep (maximum) burial depth and diagenetic changes in the carbonates, the reservoir quality will be dependent on the secondary porosity resulting from karstification, dolomitization and fracturing. Based on this evaluation, 5 prospective areas have been identified. The key risks are high temperatures leading to over-mature source rock and drilling hazards, gas quality (high Nitrogen content) and leaching by faults, for the seal must have been present at the end of the Carboniferous and must have been preserved. Would these leads not be gas bearing, then Enhanced Geothermal Systems (EGS) for a binary electricity generating system could be a fairly good option for these hot, ultra-deep leads.

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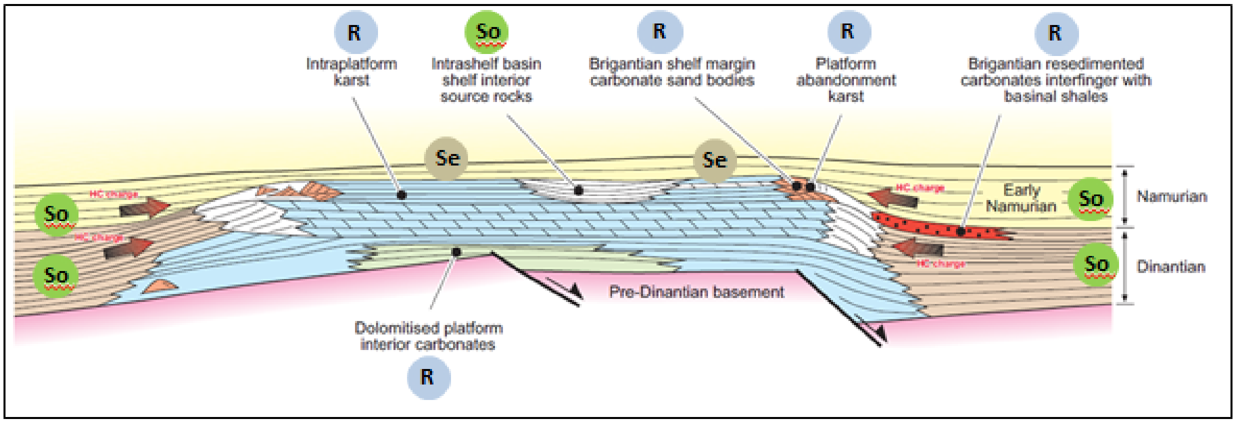
Introduction

An as of yet unproven petroleum system may be present in Carboniferous Dinantian carbonates of the Dutch subsurface. However, because of a lack of well control and the significant depth of burial of the Dinantian in large parts of the Netherlands, pre-Silesian formations have been penetrated in a limited number of wells only, and the Dinantian Carbonate play is consequently under-explored. Furthermore, seismic definition below the widespread Permian Zechstein evaporates is often very poor (van Hulten and Poty, 2008), this is also caused by lack of interest below the Rotliegend (Permian) interval, therefore seismic acquisition and processing at that depth is limited. Even though no hydrocarbon accumulations have been encountered so far in the pre-Silesian, the post-Caledonian part of this succession is still considered as potentially prospective for hydrocarbon exploration (Cameron and Ziegler , 1997). In the South-East of the Netherlands, mineral water is produced from Dinantian deposits in Well Thermea 2000 for a spa. In this region, several other wells also encountered mineral water (NITG, 1999). In Northern Belgium, the saline aquifer in Dinantian carbonates is used for the extraction of geothermal energy (Beerse-Merksplas doublet), and for the storage of natural gas (Heibaart dome in Loenhout). (Geluk et al., 2007). In the onshore UK hydrocarbon discoveries were made in the Dinantian carbonates and also the Tengiz field in the Caspian Sea, Kazakhstan is one of the largest oil producing fields from this play.

In the Netherlands, the Dinantian carbonates in the Northern onshore have attracted some interest from the oil and gas industry. In 2002 NAM drilled a first well to test the hydrocarbon potential of the Dinantian in Groningen: Uithuizermeeden-02 (UHM-02), but no hydrocarbons were encountered in this very tight Dinantian carbonate sequence. In 2004 TOTAL drilled a well to the same objective in the Noord-Oost polder: Luttelgeest-01 (LTG-01). Also this well failed to encounter hydrocarbons, and the interest of the oil and gas industry seems to have declined after these 2 wells. With the exception of the Total report on this play in November 2007: “A regional review of the Dinantian Carbonate play: Southern North Sea and onshore UK”, no detailed studies in the Netherlands have been published so far.

This report aims at giving a modern and up-to-date summary of the remaining potential of the Dinantian play in the Dutch Northern onshore. The study is based on mapping of the Dinantian and Namurian sections in the limited and rather poor-quality seismic data that is available. The seismic data is tied to the well data. Carbonate features and relevant faults are mapped to help analysing Dinantian carbonate reservoir potential, and for analysing source and seal presence in the onshore Northern Netherlands.

The current understanding of the Dinantian carbonate play is that a phase of post-Caledonian extension created a horst and graben system. Carbonate platforms developed on the highs (see figure 1), while basinal (deep water) shales were deposited in the lows in between the highs. In figure 2 the outline of the presumably Dinantian carbonate platforms are displayed (Van Hulten 2012). It is generally thought that organic-rich basal Namurian shales onlapping the Dinantian carbonate platforms could have provided hydrocarbon charge to the Dinantian limestones. The Namurian shale deposits are known to have high TOC’s and some shale deposits are even referred to as “hot shales”. Overlying Namurian or Westphalian shales are potential seals. Figure 1 shows a schematic picture of the play concept with key elements.



Structure	(faulted) carbonate platform
Source	Namurian / Dinantian shales (lateral migration)
Reservoir	karstified / fractured (Visean) limestone
Seal	Namurian shales (top / side seal)

Fig. 1: Conceptual reservoir model of the Dinantian carbonate play. (http://www.nlog.nl/resources/Posters/prospectfair2012/Poster8_Prospex%202012.pdf)

The evaluated area comprises of the Northern onshore of the Netherlands, consisting of the provinces: Friesland, Groningen and the Noord-Oost Polder (blue outline on Figure 2). The outline is based on a regional, merged 3D seismic cube; TerraCube onshore. Also 2D seismic data in the area of Southwest Friesland and Noord-Oost Polder has been used. Although the Netherlands have a database of 23 wells that reached Dinantian aged rocks, only 2 wells within the research area reached the Dinantian carbonate succession: Luttelgeest-01 (LTG-01) and Uithuizermeeden-02 (UHM-02). These 2 wells have been used for seismic mapping of the Dinantian paleo-surface. Other wells have been used to characterizing Dinantian log response and to understand the diagenesis and fracturing which can have an impact on the Dinantian carbonates reservoir qualities. Also well and-log data of wells that reached Namurian aged rocks have been used for seal mapping and for assessing potential sealing capacity. Furthermore a regional tectonic setting is discussed for source rock area and analogues have been used in order to discuss reservoir potential.

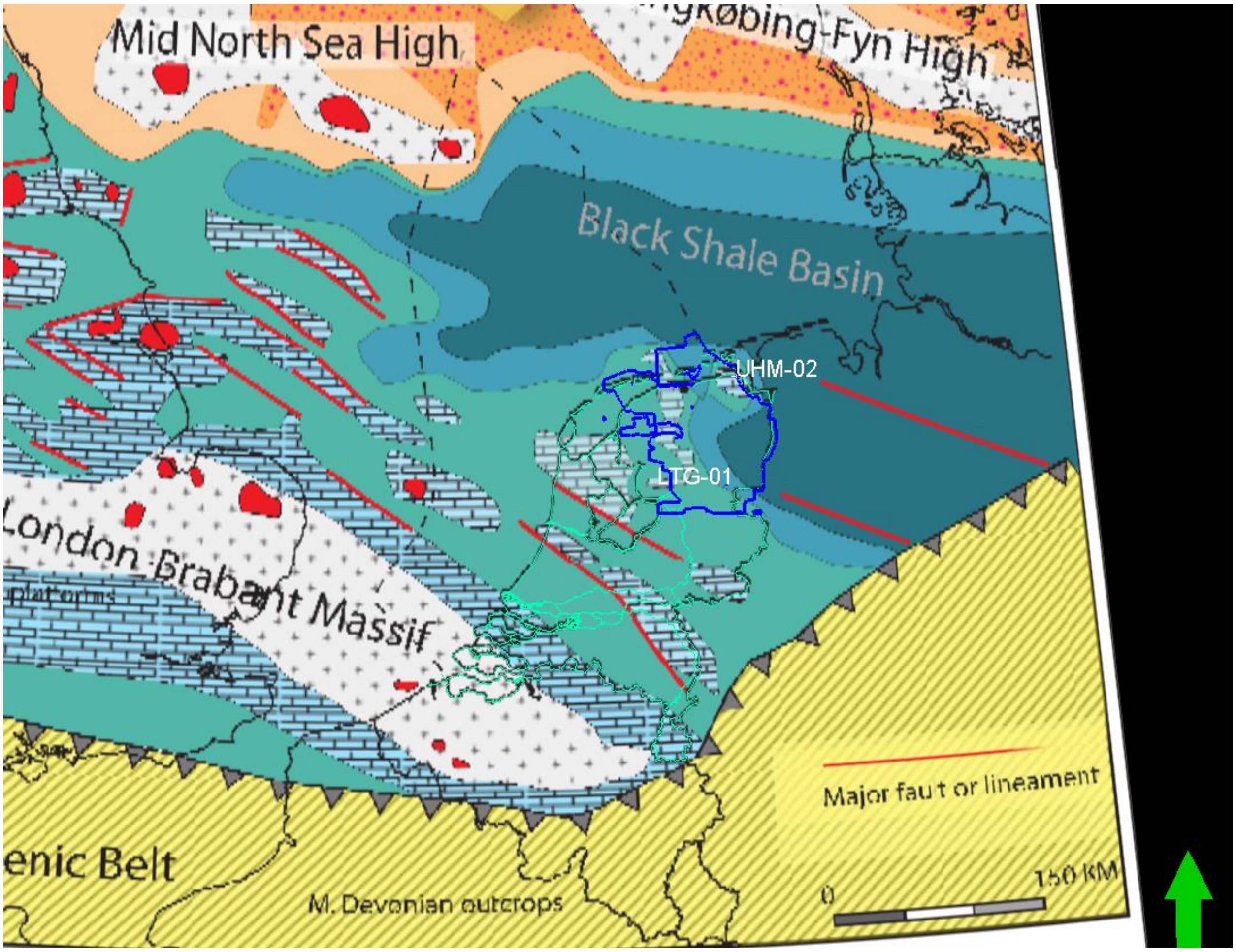


Fig. 2: Dinantian paleogeography map. Outline of the Netherlands border including: 3D seismic data (blue polygon), the wells Luttelgeest (LTG-01) and Uithuizermeeden (UHM-02), regional structural fault orientation (red stripes), outline of Dinantian carbonate platforms (white bricks), Variscan thrust front (thrust annotation) and London-Brabant Massif (white crosses). From Van Hulten, 2012 (slightly modified).

This research has been carried out as part of an exploration project at EBN Utrecht supervised by Bastiaan Jaarsma, and as a master thesis at the VU University Amsterdam supervised by Prof. Dr. Jan de Jager.

This paper is subdivided into the chapters: Geological history, Methods, Results, Conclusion and Discussion. The methods used are: Seismic interpretations (2D and 3D using Petrel software and data from www.nlog.nl), a Petrel study to identify leads, well correlations (using well logs and core & cutting information), a literature study on carbonate production in the Carboniferous and a literature study on analogues.

Geological History of the Netherlands relating to Dinantian development

The geological history of the Netherlands before the Variscan orogeny is a theoretical one because detailed seismic analyses are very limited. For understanding the pre-Variscan structural framework it is important to focus on known Caledonian structural elements (Van Hulten and Poty, 2008). The Netherlands are a part of the present day Eurasian continental plate. Before the Caledonian orogeny, its deeper crust belonged to the micro-plate called Avalonia. It became part of the Laurussian plate in the Silurian. The collision took place during an early phase of the Caledonian orogeny and resulted in the fusion of the Baltica plate with the Avalonia terrain (Van Hulten, 2012). This basin was occasionally affected by tectonic events far outside the Netherlands. It is widely accepted that a large part of the plate-tectonic amalgamation of North-West Europe was completed before Silesian times. Figure 1 and 2 shows the International Stratigraphic chart with timing of the orogenies and details on the Carboniferous. The Caledonian orogeny , recently redifined by McKerrow et al (2000a), represents the closure of the Iapetus and Tornquist oceans between three micro continents: Laurentia, Baltica and Avalonia with the Netherlands situated on Avalonia. This will be further explained in the following subchapters: tectonic history, stratigraphy of the Carboniferous and Stratigraphic Nomenclature of the Netherlands.

Chronostratigraphy					Lithostratigraphy		
Global			Local		(South)	The Netherlands	(North)
Palaeozoic	Permian				Zechstein Gp.		
					Rotliegend Gp.		
	Carboniferous	Pennsylvanian	Silesian	Stephanian	Limburg Group		
				Westphalian			
				Namurian			
		Mississippian	Dinantian	Viséan	Zeeland Formation	Unnamed shale facies	Farne Group
				Tournaisian			
	Devonian				Banjaard Group		Old Red Group
	Silurian, Ordovician and older				Caledonian basement (unnamed, largely unknown)		

Fig. 1: L*ithostratigraphic and chronostratigraphic chart with detail on the Carboniferous, from Van Hulten and Poty, (2008).*

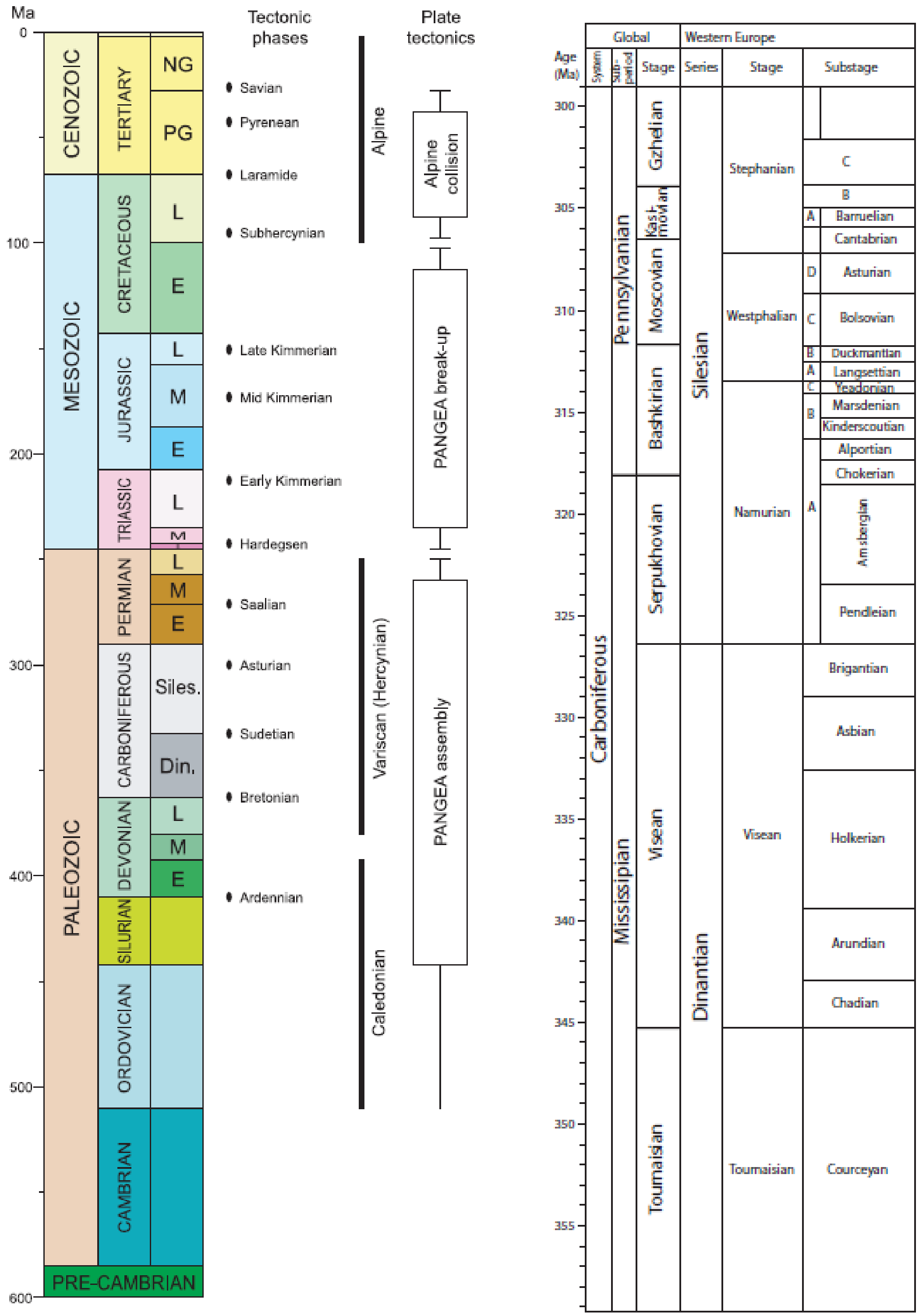


Fig. 2: stratigraphic overview and timing of plate tectonic phases. On the right side The Carboniferous is specified. after (De Jager, 2007) and (Gradstein et al., 2004).

Tectonic history

Introduction

As described above; the Caledonian Orogeny consists of the merge of three micro continents Avalonia, Baltica and Laurentia (see figure 3). At the end of the Ordovician Avalonia and Baltica collided, resulting in the closure of the Tornquist Ocean. Shortly after that during Silurian times they collided with Laurentia, causing the subduction of the Iapetus Ocean. These three micro continents together are referred to as Laurussia. An overview of the positions of these micro continents can be found in figure 3. The Variscan orogeny started in late Devonian/early Carboniferous when Laurussia collided with Gondwana to form the supercontinent Pangea, this caused the closure of the Rheic Ocean. The closure of the Rheic Ocean resulted in a fold and thrust belt called the Rhenohercynian zone. The Suture between Gondwana and Laurussia is referred to as the Variscan front. Parts of Avalonia in particular directly to the South and East of the Netherlands, are obscured by the over thrusting during the Variscan orogeny 20 Ma later (Van Hulten, 2012).

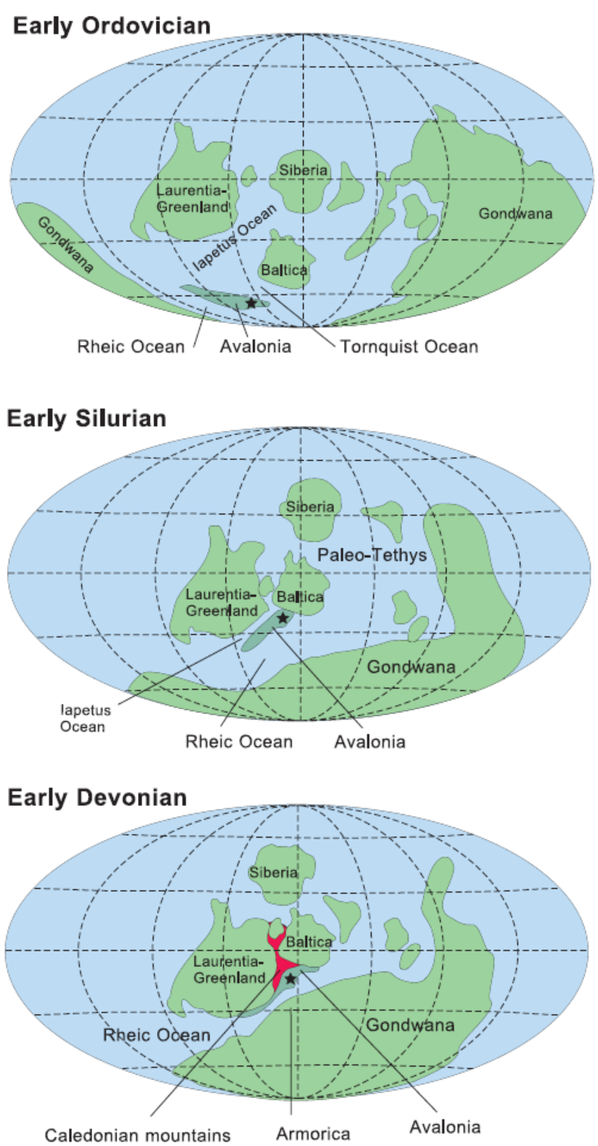


Fig. 3: Plate-tectonic reconstructions illustrating the Northward drift of Avalonia and its collision with Baltica and Laurentia. The star indicates the paleo-position of the Netherlands. From (Geluk et al., 2007).

Early Devonian

There is little data on the Early Paleozoic and the Late Precambrian history of the area of interest. There are no Lower Paleozoic outcrops and the oldest sedimentary rocks drilled by wells are not older than Silesian. Based on data from other areas (e.g. UK, Baltic Shield) and on literature, a general picture can be obtained. Most authors (De Jager, 2007. And references therein) agree that the dominant events during the Paleozoic, responsible for the overall tectonic framework, are the Caledonian (550-400 Ma) and Variscan (400-300 Ma) orogenies (Kombrink, 2008). At the end of the Silurian, the Caledonian Orogeny is closely followed by the onset of an extensional tectonic regime in the early Devonian due to back-arc extension (Ziegler, 1990), which initiated WNW-ESE trending, fault-bounded, half-grabens in the Southern North Sea (De Jager, 2007). Many of these Devonian basins formed through the reactivation of earlier Caledonian lineaments and thus have strike and dip directions similar to the underlying Caledonian thrust faults. These structural anisotropies e.g. thrust faults and major folds in the basement are assumed to be the predominant control on the subsequent orientation of later sedimentary basins and deformational structures in the overlying cover sequence, see figure 4.

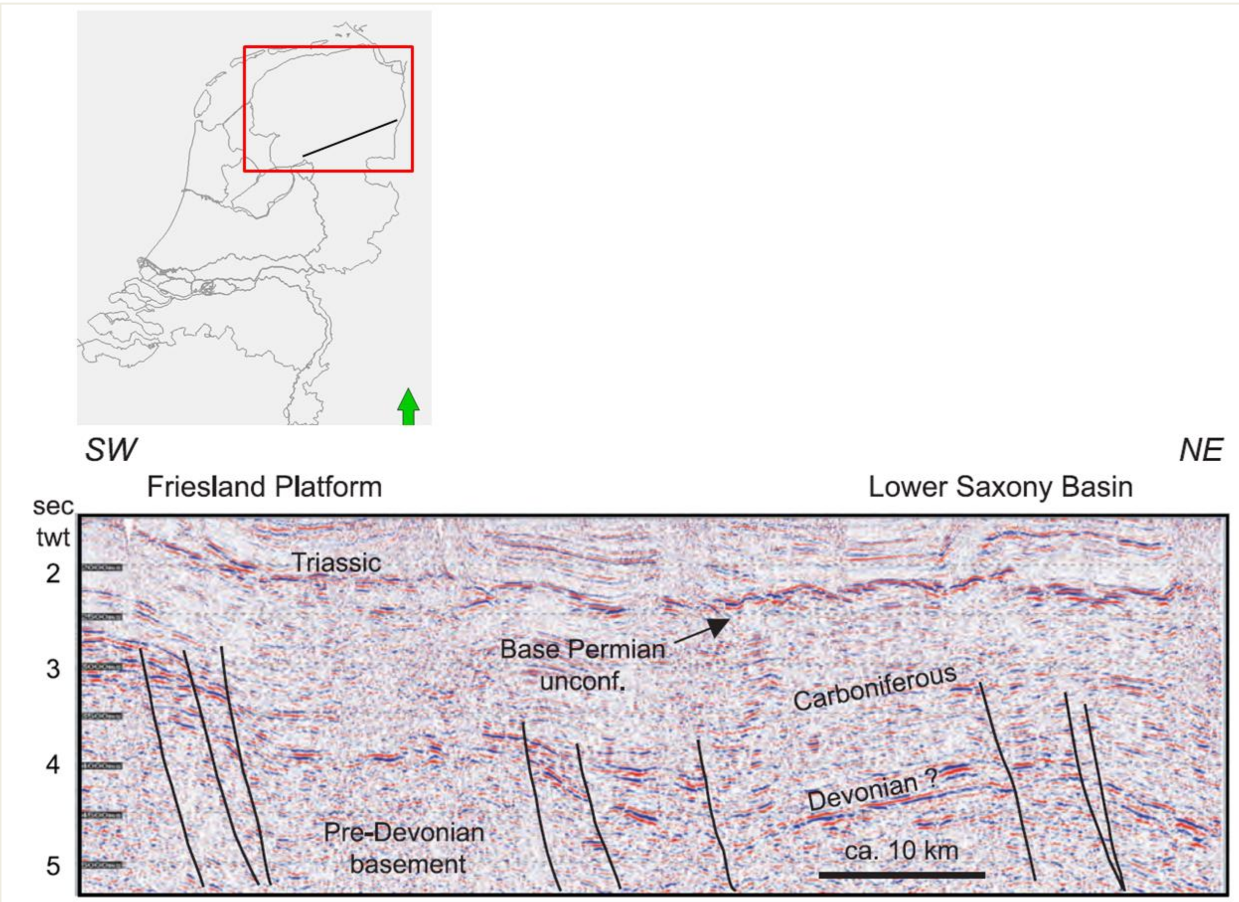


Fig 4: Deep seismic line across the Eastern Netherlands. At pre-Carboniferous levels several major tilted fault blocks indicate significant early extensional faulting. (De Jager, 2007). Black line is the emplacement of the seismic line and the red square indicates the location of the study area.

Late Devonian

Although these early extensional basins are not very well documented at all in the Dutch subsurface, and their orientation is essentially unknown, there are theories about orientation and what controlled them. These following theories are based on analogues from the UK (where these basins are better documented) and remain very speculative for the Dutch subsurface. Various tectonic models attempt to explain the driving mechanism behind Late Devonian/Early Carboniferous crustal extension in NW Europe. Leeder (1982) attributes the rifting to back-arc extension resulting from the Northwards directed subduction-related rollback, of the closure of the Rheic oceanic crust. The result of which is a failed back-arc rift basin in Northern England. Coward (1990, 1993) and Maynard et al. (1997) prefer a model invoking crustal escape tectonics as an alternative cause for crustal extension. It has been argued (Maynard et al., 1997) that a simple two-phase tectonic model for the Carboniferous basin evolution consisting of a back-arc related North-South extension followed by a thermal sag phase (starting in the Namurian) appears to be oversimplified. Coward (1990 and 1993) proposed a regional model which involves escape tectonics of a triangular plate fragment named the North Sea-Baltic block, comprising the present North Sea area, the Baltic area, and most of Britain and Scandinavia. During the Devonian and Early Carboniferous this block would have been squeezed out in an Eastward direction from the colliding plates of Gondwanaland and Laurentia . The implications of this model obviously are important strike-slip components in the movements. The prevailing stress regime would have been dextral transtension along the Southern boundary of the block (close to the southernmost part of the North Sea area) and sinistral transtension along the Northern systems. The release from the indenter also allowed the block to expand in the NW-SE direction. Maynard et al. (1997) noted that the configuration in the Early Carboniferous may have been quite similar to what can be observed today in the Eastern Mediterranean, where the Turkish and Greek plates are in a process of Westward translation. A detailed 3D seismic interpretation of the Cleaver Bank High showed the presence of dominant East-West shear zones that are not always visible at first glance, because they have been frequently reactivated throughout the Paleozoic and Mesozoic (Schroot & de Haan, 2003). These zones and the observation of strike slip movements along them fit the model proposed by Coward.

Independent of the mechanism, the result of Late Devonian/Early Carboniferous extension was the development of a series of extensional grabens and intervening platform areas to the North of the London-Brabant Massif in a belt extending from Belgium through the Netherlands (and the study area) and the Southern North Sea and into onshore UK and Ireland. The trends of these features were controlled by the deep Caledonian thrust fault systems. There was pulsed rifting during the Dinantian which was interspersed by quieter, stable tectonic periods. See figure 7 for paleotopography of the Dinantian and orientation of major fault lineaments.

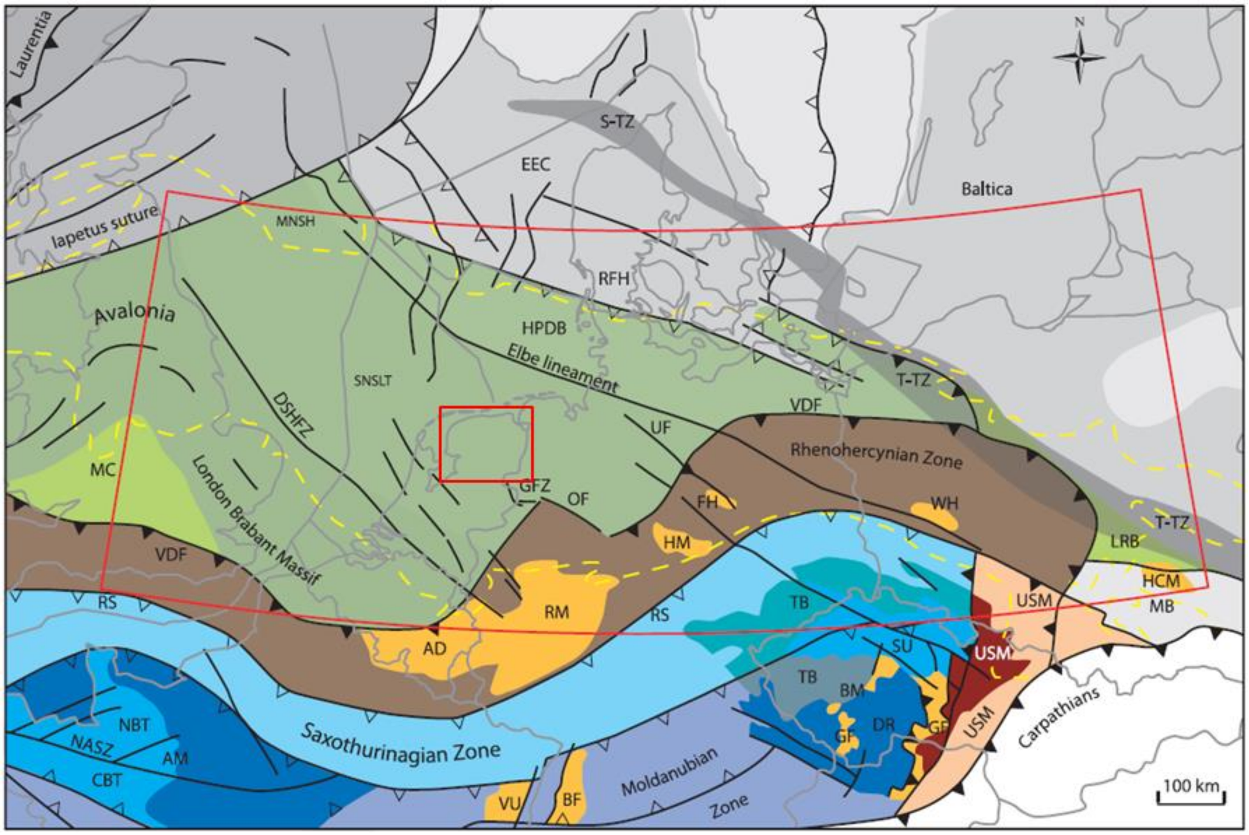


Fig. 5: Structural elements of the North West European Carboniferous Basin. Small red square indicates the study area. The grey areas represent Laurentia and Baltica. The greenish central part of the map indicates the Avalonian microcontinent. The Rhenohercynian Zone represents the external fold and thrust belt of the Variscan orogen that was thrusted onto the Southern margin of Avalonia. Orange: areas of outcropping Carboniferous rocks. The bluish zones form micro-continents accreted during the Variscan orogenic cycle. The yellow dashed line indicates the extent of Carboniferous rocks in the Southern Permina Basin area. Oceanic sutures, open ticks; orogenic frontal zones, filled ticks.
Key: Post-Palaeozoic platforms: MNSH: Mid North Sea High, RFH: Ringkobing-Fyn High. Postulated Palaeozoic terranes and possible terrane/sub-terrane boundaries: CBT: Central Brittany Terrane, DSHFZ: Dowsing-South Hewett Fault Zone and continuation in Roer Valley Graben (SE), GFZ: Gronau Fault Zone, OF: Osning Fault Zone, RS: Rhenohercynian Suture Zone, SNSLT: Southern North Sea Luneburg Terrane, LRB: Łisogory-Radom Block, MB: Malopolska Block, UF: Uelzen Fault. Proterozoic-Palaeozoic tectonic elements: AD: Ardennes, AM: Armorican Massif, BF: Black Forest, BM: Bohemian Massif, DR: Drosendorf Unit, EEC: East European Craton, GF: Gfohl Unit, HCM: Holy Cross Mountains, HM: Harz Mountains, MC: Midland Craton, NBT: North-Brittany Terrane, RM: Rhenish Mountains, S-TZ: Sorgenfrei-Tornquist Zone, SU: Sudetes Mountains, TB: Tepla-Barrandian Basin, T-TZ: Teisseyre-Tornquist Zone, USM: Upper Silesian Massif, VDF: Variscan Deformation Front, VU: Vosges Unit, WH: Wolsztyn High. (Kombrink, 2008).

Early Carboniferous

The Late Devonian/Early Carboniferous tectonic extension became East-West in the British onshore, bending to SE-NW in the SNS and the Netherlands (Besly, 1998). Fraser & Gawthorpe (1990) noted that during the late Devonian rifting phase the North-South extensional stress regime reactivated both the NW-SE and the NE-SW trending zones of weakness, which had been inherited from the Caledonian orogeny. Strongly asymmetric grabens were formed. East-West trending basins have been well described on the British onshore (De Jager, 2007). Similar structural style can also be applied in the Belgian Campine Basin (Dreesen et al, 1987: Muchez and Lanenaeker, 1993). In the Netherlands, a general NW-SE fault pattern is assumed to be of pre-Variscan origin (Schroot et al., 2006). This was based on the structural trends in the Dutch Northern offshore, see figure 5. These trends can also be observed in major Dutch structural elements onshore like the Texel-Ijsselmeer High and Maasbommel High and also West Netherlands Basin follows this orientation. This pattern more or less parallels the Tornquist Suture and can be explained by continued reactivation of this Lower Paleozoic trend in extensional, compressional and strike-slip regimes (Fraser and Gawthorpe, 1990). A characteristic feature for this structural style is the forming of half grabens, see figure 6. It has to be noted, though, that half grabens with their tilted block tectonics cause problems for regional correlation of Devonian or Lower Carboniferous strata when there are only a few wells present (Muchez and Langenaeker,1993). Layers in the high part of the block can be eroded and will then be missed by a well. (Poty and Van Hulten 2008).

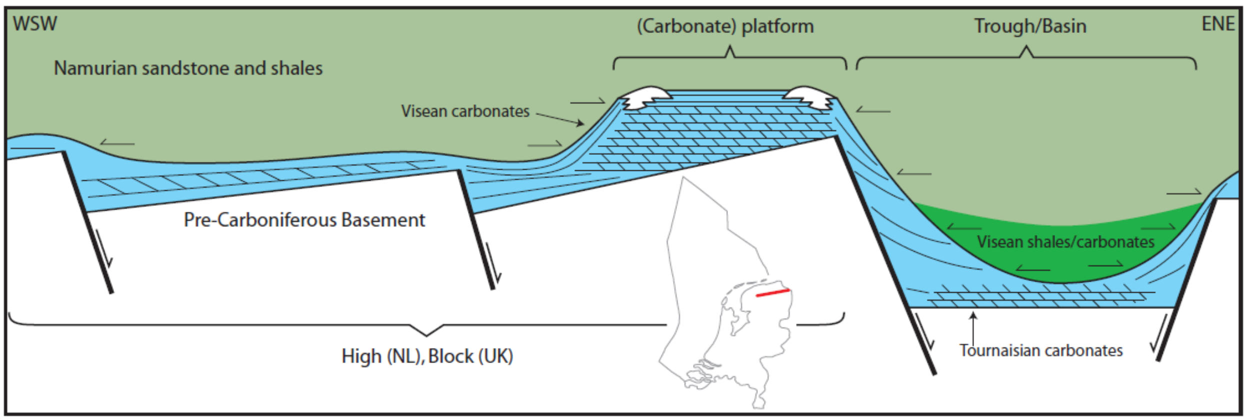


Fig. 6: Schematic cross-section showing the structural and stratigraphical setting in the study area in the Dinantian (Kombrink, 2008).

Late Carboniferous

Traditionally, the Namurian to Westphalian C is considered as a long period of relative tectonic quiescence in the basin. This period of roughly 20 Ma was earlier described as a classical sag phase, with sedimentation gradually burying the underlying rift topography such that the study area was covered by major deltaic systems during Westphalian. (Total, 2007. And references therein). However, tectonic events affected the area, evidence has been found by Schroot et al. (2006) for an intra-Namurian angular unconformity on seismic, The interpreted surface could imply both erosional truncation and onlap onto that surface. In a few Dutch wells there is evidence of Namurian volcanism (Nag-01), which may mean local crustal thinning. All things considered, it is evident that simple sag model is too simple. Active tectonics during the Namurian should be taken into account.

At the end of the Westphalian the tectonic movements of the Saalian event affected the deposition of strata during the Stephanian and Early Permian. In Germany and in the East Netherlands, Stephanian sediments unconformably overlie the Westphalian (Ziegler, 1990). It is likely that Stephanian rocks had a much wider distribution, but were eroded in large parts during the Early Permian uplift (Saalian event) caused by Wrench faulting associated with intrusive and extrusive magmatism and thermal uplift (De Jager, 2007). For instance, thermal modeling in the Ruhr area showed that a thick sequence of Stephanian rocks might have been present (Schroot et al., 2006). The NW-SE trend that was already established by mid-Paleozoic times was reactivated in response to Early Permian wrench deformation while regionally a conjugate set of NE-SW to NNE-SSW faults developed (Ziegler, 1990).

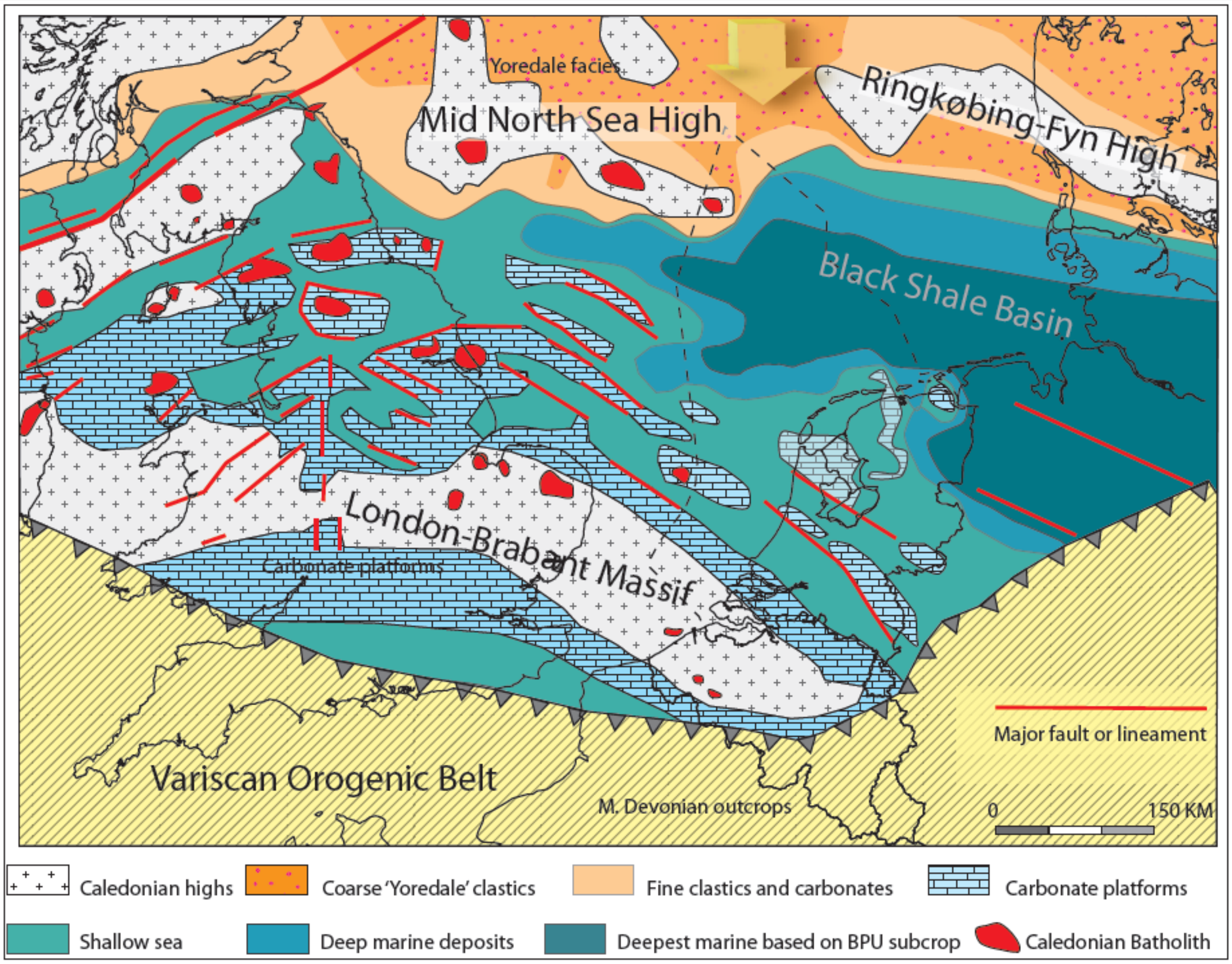


Fig. 7: Paleotopography during the Dinantian, (Van Hulten, 2012).

Triassic-Jurrasic

By late Permian times a new tectonic regime had become established in Northwest Europe. Widespread regional thermal subsidence following the Variscan collision led to the development of the Southern Permian basin in the region of the Southern North Sea. Rifting related to the Mesozoic break-up of the Pangea supercontinent, called the Kimmerian rifting phase, commenced during the Triassic in the Arctic-North Atlantic and between Greenland and Scandinavia, and slowly propagated southwards into the Central Atlantic domain along the line of future continental break-up. An Eastern branch of crustal extension propagated during the Early Triassic into the North Sea area (Ziegler, 1990). During the Middle Triassic, the extension had reached the Southern North Sea, although the degree of extension rapidly decreased Southwards. (De Jager, 2007). The NW-SE orientation of the Mesozoic extensional basins in the South and West of the Netherlands does not conform to the assumed E-W direction of extension during Late Kimmerian rifting. Thus their localization was probably controlled by pre-existing pervasive structural elements (De Jager, 2007), such as those of the Caledonian orogeny.

Cretaceous-Tertiary
During the Late Cretaceous, Africa-Arabia began to converge with Eurasia and the Tethys system of oceanic basins started to close. This resulted in the gradual development of the Alpine orogenic system. This affected the offshore in the Southern North Sea as a post-Jurassic phase of inversion and erosion. Inversion-related uplift of the basins resulted in depositional thinning and in erosion of the Upper Cretaceous chalk and Lower Tertiary clastics, as well as in local truncation of older sediments. On the flanks of the basins, thinning of Upper Cretaceous or Lower Tertiary deposits towards the inversion axes shows uplift to have been a continuous process, although with several acceleration pulses. These pulses seem to have been simultaneous in most inverted basins (De Jager, 2007).

London-Brabant Massif
As seen on figure 7 and as mentioned in this the chapter the London Brabant Massif holds a special place in the forming of pre-Silesian structure of the Netherlands. It is believed that it represents the stable area against which the Variscan orogeny abutted (Geluk et al., 2007). During the Ordovician and Silurian, the oceanic Iapetus plate subducted below Laurentia and Avalonia. In North Wales and in the Lake District in Northern England, calcalkaline magmatism occurred during the Middle to Late Ordovician, testifying to this subduction. The Late Ordovician calcalkaline magmatic rocks in Anglia and the inferred granites in the Brabant Massif are probably also related to subduction, although the paleogeographic context is less clear in these cases. Deep seismic profiles in the Southern North Sea (Blundell et al., 1991) revealed a SW-dipping deep reflector in the mantle which was interpreted as a possible remnant of this Ordovician subduction zone. The Brabant Massif consists of little deformed Middle Devonian strata overlying stronger deformed Lower Paleozoic meta sediments. The structure of this massif shows a WNW-ESE oriented Cambrian core curving Eastwards to an E-W direction and surrounded on both sides by Ordovician and Silurian rocks. A low-grade epizonal metamorphism affects most of the massif, except its South-Western part. There is no systematic difference in metamorphic grade between Cambrian, Ordovician and Silurian rocks, but towards the North and the South this grade diminishes, regardless of the ages of the rocks involved. As outcrops appear only in some river valleys in the South of the Brabant Massif, subcrop mapping has been carried out based on extensive borehole data, helped by the interpretation of aeromagnetic and gravity maps (Geluk et al., 2007. And references therein).

Stratigraphy of the Carboniferous

Introduction

The top of the pre-Silesian in the Netherlands varies considerably in depth. In the South-Easternmost tip of the Netherlands, it lies just above the Dutch Ordnance Level (NAP), whereas in the nearby Roer-Valley Graben and in the central and Northern offshore, it is situated below 9000 m.

The pre-Silesian succession can be subdivided into two parts:
1-A Precambrian to Silurian, weakly metamorphic, moderately deformed Caledonian succession/basement. This is based on information from Belgian wells only since there are no Lower Paleozoic outcrops and the oldest sedimentary rocks drilled by wells in the Netherlands are not older than Silurian. (Geluk et al., 2007).
2-An overlying post-Caledonian, Middle to Upper Devonian and Lower Carboniferous, mildly deformed succession of sediments.

The Caledonian basement is largely unknown. The post Caledonian sediments are subdivided in:
-Devonian: Old Red Group and Banjaard Group.
-Lower Carboniferous: Farne Group (clastic sediments) and Carboniferous Limestone group (carbonate sediments). See figure 8 for an Schematic stratigraphic overview of the pre-Silesian.

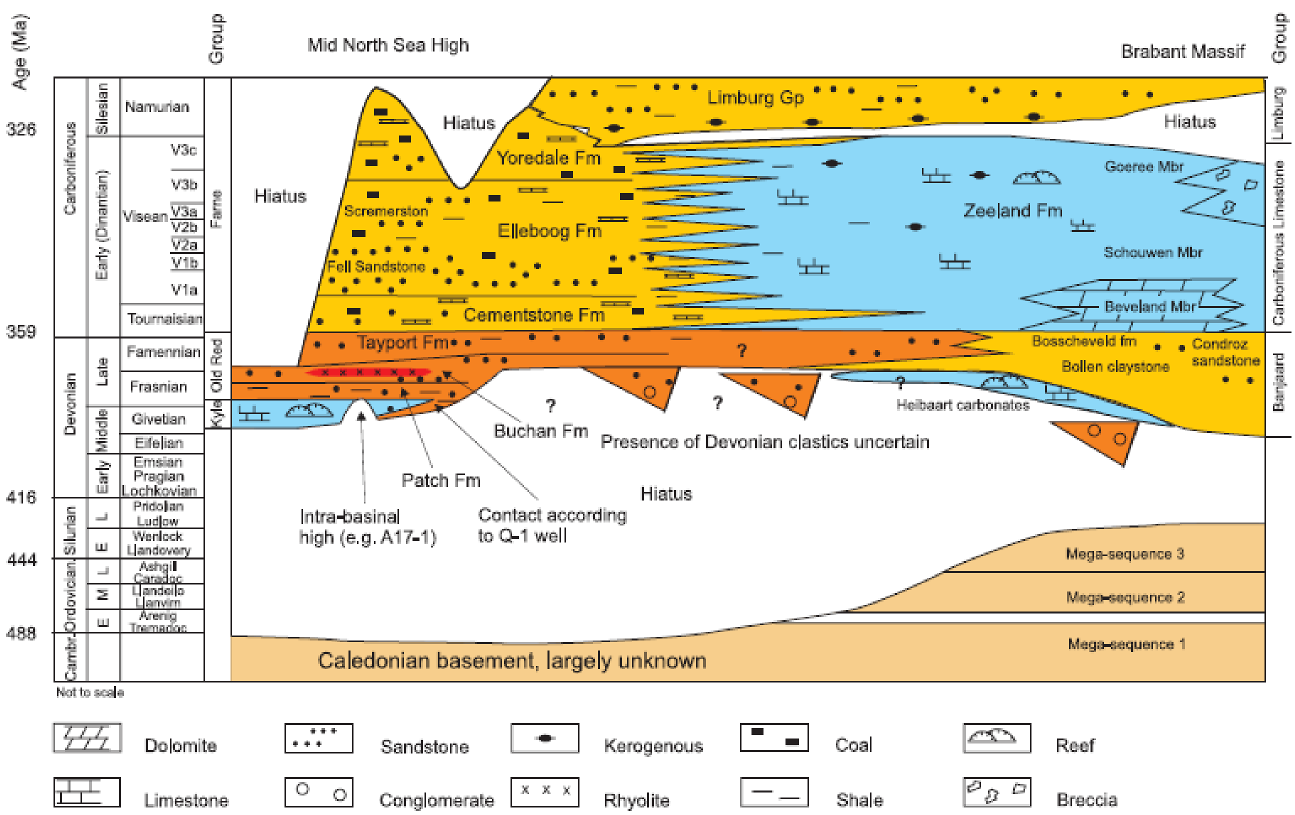


Fig. 8. Schematic stratigraphic overview of the pre-Silesian, Cambrian to Lower Carboniferous deposits in the Netherlands and surrounding areas. Well data used for calibration are only available for the Mid North Sea High and the Brabant Massif. The stratigraphy in the area in between is highly speculative. (Geluk et al., 2007).

Dinantian

During the Dinantian much of Europe was characterized by the development of platform carbonates and deep marine shales and chert layers in areas of low clastic input (Schroot et al., 2006)). Areas in the vicinity of clastic sources were dominated by shallow deltaic, deep-water deltaic and turbidite deposition. Many of the major late Paleozoic basins in other parts of the world are characterized by a similar history. The structural setting during the Early Carboniferous had a large effect on the Dinantian deposition. The highs were preferential sites of carbonate-platform deposition. The lineaments of these highs followed the old Iapetus and Tornquist sutures. The flanks of the London-Brabant Massif also constituted such highs.

Carbonates from Dinantian outcrops across Western Europe have been intensely studied. These carbonates developed on structural highs. In general, deposition failed to keep up with the rapid subsidence of basement blocks. This caused the progressive shift from shallow-water ramp deposition to deeper-water steep-margined platform deposition, see figure 9 (Total, 2007). Consequently the margins of carbonate platforms were becoming steeper through time. In total 6 sequences have been identified, see table 1.

Age and Sequence	Log Character	Environment
S6: Brigantian; $4/5^{th}$ order glacio-eustatic cycles.	**Shelf:** cyclic, moderate gamma carbonates with gamma spikes. **Slope:** spikey gamma. **Basin:** high gamma.	**Shelf:** low energy cyclic subtidal shelf carbonates with karst at cycle boundaries. **Slope:** carbonate boulder beds and shale **Basin:** shales with carbonate turbidites.
S5: Asbian; $4/5^{th}$ order glacio-eustatic cycles.	**Shelf:** cyclic with clean carbonates and gamma spikes, high gamma palaeosols. **Slope:** spikey gamma. **Basin:** high gamma.	**Shelf**: cyclic subtidal shelf carbonates with karst and palaeosols at cycle boundaries. Grainstones near shelf margins. **Slope:** local boulder beds of shelf carbonates interbedded with shales. **Basin:** shale and carbonate turbidites.
S4: Holkerian; a single 3^{rd} order sequence. Local erosion at top.	High gamma TST and MFS, low gamma TST/early HST, higher gamma late HST.	**Shelf:** Low energy non-rimmed carbonate shelf with peritidal shelf interior facies. **Basin:** deep to mid carbonate ramp.
S3: Arundian; at least 5 4^{th} order sequences that onlap basement and earlier cycles.	Aggradational TST with maximum flooding interval, progradational HST.	Basal mixed siliciclastic-carbonate marginal marine sequence then progradational carbonate ramp. Sequences separated by sequence boundaries. Carbonates are often dolomitised.
S2: Chadian to Arundian; at least two 4^{th} order sequences that onlap basement and earlier sequences.	Aggradational TST with maximum flooding interval, progradational HST.	Fluvial, marginal marine and near shore siliciclastics and carbonates, rare evaporites. Carbonates often dolomitised.
S1: Tournaisian to Chadian; at least one 4^{th} order cycle that onlaps basement.	Aggradational TST with maximum flooding interval, progradational HST.	Fluvial, marginal marine and near shore siliciclastics and carbonates. Carbonates often dolomitised.

Table 1: Dinantian sequence stratigraphy, (Total, 2007).

Locally deeper-water environments were occupied by so-called Waulsortian build-ups; these structures are mud mounds with initial vuggy porosity (Total, 2007).
Five mound associated facies have been identified in the Dinantian carbonates: 1. mound core, 2. mound flank (fine), 3. mound flank (coarse),4. intermound (fine) and 5. intermound (coarse), (P. Bridges and A. Chapman, 1988).

1. The mound core facies is a massive skeletal wackestone with comminuted sponge debris, foraminifera, ostracodes and crinoid debris set in a matrix of clotted micrite.
2. The mound flank sediments display moderately inclined bedding surfaces. While the mound flank (fine) contains sponge debris.
3. the mound flank (coarse) is dominated by articulated crinoid columns, and includes algal-encrusted micritized intraclasts and coarse peloids.
4. The well-bedded intermound (fine) facies is bituminous and micritic while the
5. intermound (coarse) facies is composed of skeletal-peloidal-intraclasts grainstones which locally contain calcified algae.

In general these build ups are not reefal frameworks and they comprise micrite with low permeability and vuggy porosity and they are often dolomitized (by fluids derived from connate waters expelled during compaction of mudstone sequences). In places the carbonate system was drowned near the end of the Visean when carbonates were overlain by organic-rich shale and chert (Bless et al., 1976).

The Dinantian is subdivided into three main chronostratigraphic units corresponding approximately to the Tournaisian, the Late Chadian-Arundian and the Holkerian-Asbian-Brigantian respectively. This division can be followed from the calcareous deposits in the South (Zeeland Formation) to the clastic deposits in the North (the Tayport, Cementstone, Elleboog and Yoredale Formations). The Tournaisian interval is often missing, or only partly developed . The upper interval is also occasionally missing implying an unconformity between the Dinantian and the Namurian. See figure 10 for the stratigraphical chart.

In the Northern part of the North Sea, the sediments were deposited in a fluvial/deltaic to shallow marine setting (a marginal deltaic facies): the Yoredale deposits. In the Dutch North Sea sector these age ranges from Chadian to Pendleian (Van Adrichem Boogaert and Kouwe, 1993-1997). These clastic deposits most-probably had a Northerly source.

Equivalent sediments in Northern England comprise stacked sequences of Yoredale cycles (Maynard & Dunay, 1999), which by Brigantian times were being deposited from the England/Scotland border to at least as far South as the Tees estuary. Yoredale deposition continued through the Pendleian into the early Arnsbergian across most of Northeastern England and persisted into the Kinderscoutian (Middle Namurian) over the Alston Block. Within the Yoredale succession thin coal seams occur. Organic matter is of Type III kerogen, with TOC contents generally between 0.89 and 1.87 %, but locally almost up to 9%. Although transgressive cyclothems with marine influences at the base could be clearly recognized, there are no marine oil prone source rocks in these deposits. Little is known about the time-equivalent sediments in the Southern North Sea away from the immediate extensions of the onshore highs and platforms (Schroot et al., 2006. And references therein).

More information on the Carboniferous Limestone group (Zeeland formation) and Farne group (Yoredale, Elleboog and Cementstone formation) can be found in the next sub-chapter: Stratigraphic Nomenclature of the Netherlands.

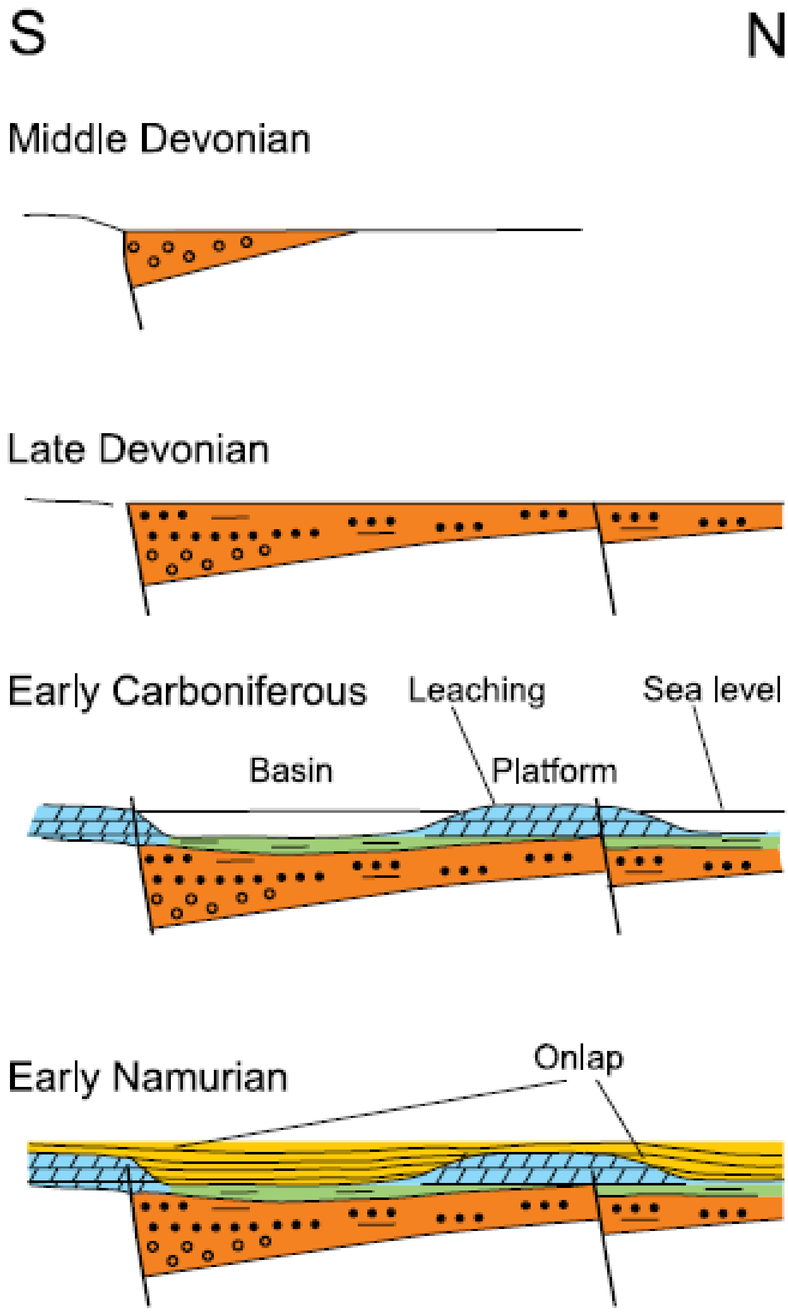


Fig. 9. Schematic model for the deposition of the Devonian and Lower Carboniferous in the area North of the London-Brabant Massif. Half-grabens controlled the sedimentation during the Middle Devonian to Early Carboniferous. Dinantian carbonate platforms reside on the footwall blocks, the hanging-wall blocks are characterized by basinal deposits. Exposure on the platforms led to karstification. The Namurian transgression progressively overstepped the platforms. (Geluk et al., 2007).

Namurian

The basin-fill comprises first the basal Namurian marine shales, draping the morphological features remaining of the half-grabens or carbonate build-ups. Subsequently, the later Namurian regression caused continental deposits from the middle Namurian onwards. The regression was related to the onset of glaciations in the Southern hemisphere and possibly also to the Variscan orogeny. During the evolution of the Variscan orogen the deformation front migrated gradually Northwards and the back-arc seaway was closed and deformed into major nappe complexes. The loading imparted by these complexes led to the formation of a flexural foreland basin, which also migrated Northwards (Schroot et al., 2006. And references therein). By the Late Westphalian this flexural foreland basin had reached its Northernmost position. The transition from the Dinantian to the Namurian is expressed by a marked drop in carbonate sedimentation in NW Europe and, in particular, in the Southern North Sea. Because the clastic sediment input in the earliest Namurian remained low, the lack of carbonates instigated sedimentation of only clays and organics. This resulted in clay sedimentation throughout NW Europe (Bowland, Pendle and Edale Shales (UK) and the Epen Formation in the Netherlands). It is suggested that these shales have been draped over the pre-existing Dinantian topography. Occasionally, these shales have high TOC values e.g. Geverik Member (see figure 11).

In the Northern part of the Southern North Sea, the deposition of the Yoredale Formation also passes into the Epen Formation. However, there is not a marked change or unconformity. On the London Brabant Massif in the South an unconformity was recognized between the Dinantian carbonates and the Namurian shales (Bless et al, 1976). On the London Brabant Massif the contact between Dinantian and Namurian is an erosional unconformity. In Zuid-Limburg, there is a hiatus present rather than an unconformity.

In the Southern part of the basin, the basal Namurian mainly developed as shale. Black shales are known from both the Lower Namurian as well as the Dinantian (Bless et al, 1976). The occurrence of black shales at the base of the Namurian sequence is proven in certain locations in the UK, the Netherlands and in Germany. These organic rich formations are referred to in the UK as the Bowland Shale Formation and the time equivalent Edale Shale or Pendle Shale (UK Nomenclature).

If the intra-platform basins existed in the Namurian, they may have contained these basal Namurian source rocks. There are not enough (published) wells to define the extent of deep-water Bowland Shale/Geverik member. However, their existence and regional development can be assumed (Maynard & Dunay, 1999). Possibly, the Dinantian carbonate platforms acted as barriers that prevented terrestrial influx into the intra-platform basins. These black shales have been interpreted as having settled from suspension in an anoxic marine basin with restricted circulation. The Dutch equivalent of these deposits is the Namurian Epen Formation, with its basal organic-rich Geverik Member (Namurian A, Van Adrichem Boogaert and Kouwe, 1993-1997). The Geverik Member constitutes the base Namurian in the Limburg area just Northeast of the Brabant-Massif. The unit consists of dark-grey or black bituminous shaly claystones, with intercalations of siltstones and very fine-grained sandstone. The age of the member is Pendleian, Namurian A.

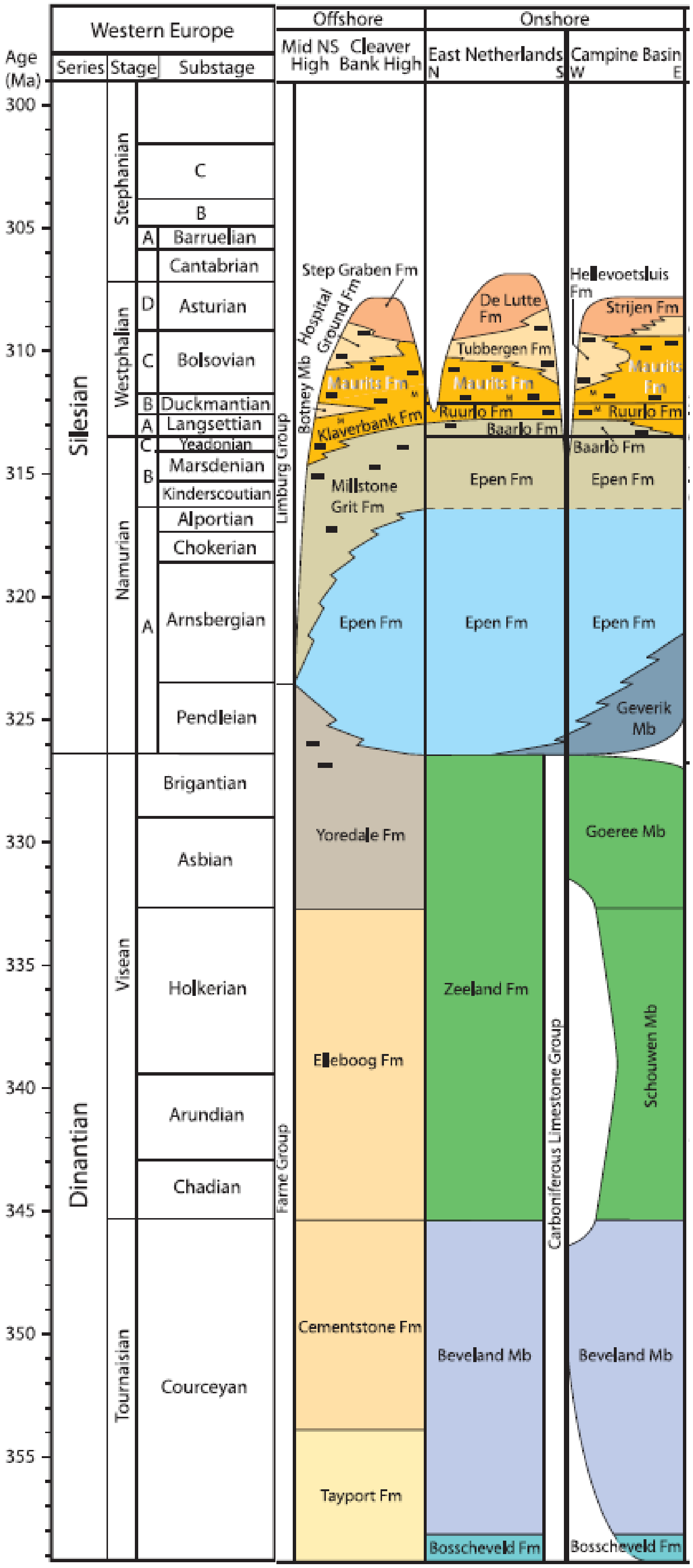


Fig. 10: Carboniferous stratigraphy (After Kombrink, 2008). Please note that the Beveland member can also be present in Early Visean, see figure 8.

A major hiatus is present in the Namurian in most wells. Biostratigraphically, the hiatus is characterized by the absence of a part of the lower interval. In general, middle Arnsbergian and older strata may be missing. The Late Namurian is mostly present. This hiatus is also confirmed by the fact that the lower interval (Pendleian - "middle" Arnsbergian) is significantly thinner developed in most areas than the upper part while it comprises a much longer time span (ca. 8 Ma). The duration of the upper part (latest Arnsbergian - Yeadonian) is significantly less (ca. 2 Ma). Despite the clear indications of a hiatus, it is not possible to pick the exact position of this hiatus by well log information only. Based on the present dataset, it is difficult to further subdivide the two intervals on biostratigraphic data. This is due to the relatively high maturation in most wells, the poor preservation of (micro)fossils and lack of good samples.

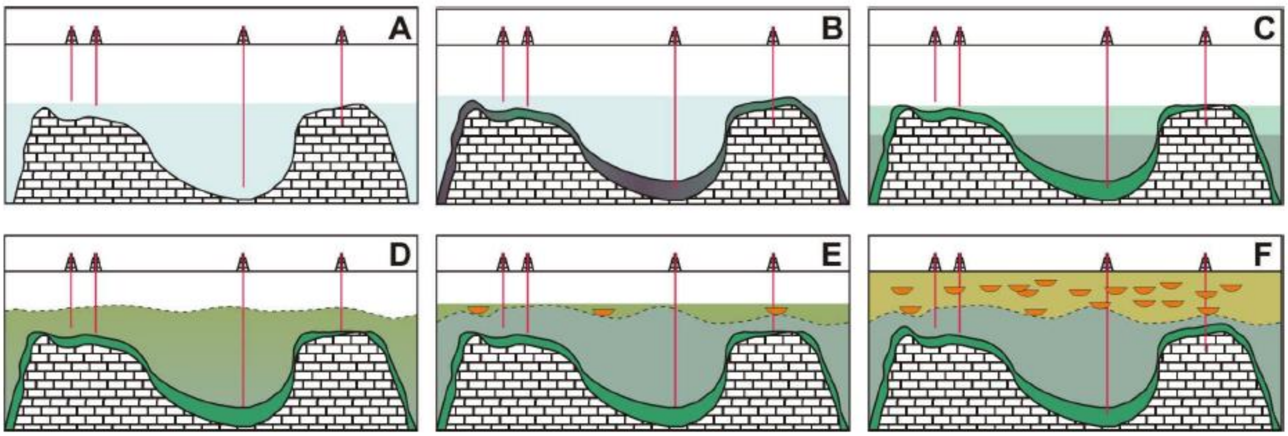


Fig. 11: Development of the Namurian including the "Geverik draping" event:
A = Late Dinantian, B = Pendleian (Geverik Mb and equivalents), C = Early Arnsbergian (Epen Fm)
D = Late Arnsbergian (unconformity), E = Chokerian, F = Chokerian – Yeadonian ("sandy" Epen Fm and base Baarlo Fm). (Schroot et al., 2006)

Stratigraphic Nomenclature of the Netherlands

All information from:www.nlog.nl

Carboniferous Limestone group

Consists of the Zeeland formation: Mainly light-grey to brownish and black limestones, and medium-grey to dark-brown dolomites. Intercalations of thin to medium-thickness fissile claystone and chert beds are common. The thickness of the formation in the Southern Netherlands varies from 900 to 1400 m. In areas where the Zeeland Formation was truncated by later erosion, the upper part of the formation may be strongly leached and subsequently silicified. An enrichment in organic carbon is frequently observed under these circumstances. The top of the formation has been placed where the calcareous deposits change into the fine clastics of the basal Epen Formation. This boundary is in many places a sharp contact. Where severe post-Carboniferous erosion took place, the Zeeland Formation can be overlain unconformably by younger formations. The base of the formation is formed by the contact with the clastic sediments of the earliest Carboniferous formation or the Late Devonian Bollen claystone.

The formation consists of 3 members: The Goeree, the Schouwen and the Beveland member locally eroded.

Goeree member:
A sequence of grey to dark-grey and black limestones, thin- to thick-bedded and often partly silicified. The limestone beds often grade into calcareous and/or silicified black shales or black cherts toward the top. Very thin beds of tuffaceous rock occur, predominantly in the upper part of the member.

Schouwen member:
A thick sequence of light to dark-grey, dark- to yellowish-brown and brownish-black, and light yellowish-brown to dusty yellow-brown limestones. The dense limestones are micritic, biosparitic to biomicritic, locally oolitic and abundantly fossiliferous. In places coarsely crystalline calcite veins occur. Intergranular bituminous, organic material is often present. Locally, the limestones are dolomitized, especially near fault zones, or silicified in the leached zone in areas where later erosion truncated the Formation.

Beveland member:
A sequence of medium-grey or brown grey to dark-brown or brown-black, coarse-crystalline dolomites, often containing black organic intergrain residues. The dolomites are generally of secondary origin. In places minor grey to dark-grey limestone intercalations occur, as well as minor quantities of dark-brown to blackish siltstone and shaly claystone. In addition, dark beds of silicified dolomite are occasionally present

Farne group

A group of claystones and sandstones with minor coal seams, and a variable amount of intercalated limestone and dolomite beds. The top of the group has been placed at the top of the highest limestone. Here the typical coarsening upward claystone/sandstone sequences of the conformably overlying Epen Formation. In areas subjected to later erosion, the group is overlain unconformably by younger formations (Rotliegend to Chalk). The group overlies the Old Red Group conformably. Its base is marked by the lowermost carbonate bed.

The Farne group consists of the Yoredale , Elleboog and the Cementstone formation.

Yoredale formation:
Cyclic alternation of limestones, claystones, sandstones and rare coal seams. The number of limestone beds is variable. The upper boundary is defined by the top of the uppermost wel developed limestone bed. The formation is overlain conformably by the Epen formation, which locally contains some minor carbonate intercalations in its basal part. The lower boundary has been placed at the base of the first distinct limestone bed overlying the clastics of the Elleboog Formation.

Elleboog formation:
Sequence of alternating claystones, sandstones and minor amounts of coal, with a few calcareous or dolomitic intercalations. The amount of sandstone tends to increase Westward. the upper boundary at the base of the lowermost limestone bed of the overlying Yordale Formation. The lower boundary has been placed at the top of the uppermost carbonate bed of the underlying Cementstone Formation

Cementstone formation:
Cyclic alternation of carbonates, claystones, sandstones and minor coal seams. The carbonates occur as limestone, dolomitic limestone and dolomite beds.

Limburg group
A group of clastic formations, forming a thick, monotonous succession of mostly grey to black, fine-grained siliciclastic sediments commonly containing intercalated coal seams in the middle and upper parts. Fossiliferous marine beds are frequently intercalated in the oldest parts, but these become scarce in the middle parts, and are absent from the youngest interval. The group also comprises light-colored, massive sandstones, and primary red-bed intervals without coal seams. Volcanic beds (mostly mm-thin tuff layers) can be intercalated locally. The basal interval commonly consists of a black, bituminous shale, locally containing silicified limestone laminae. Secondary reddening is frequently observed beneath the top unconformity. Practically all formations of the Limburg Group can be overlain unconformably by the Lower Rotliegend Group (volcanics, volcaniclastics, red beds), Upper Rotliegend Group (red-bed clastics, evaporites), Zechstein Group (claystones, carbonates, evaporites), Rijnland Group (glauconitic sands, clays, marls), or Chalk Group (glauconitic sands, marl and chalk). In the specific unit definitions these truncated situations will not be mentioned separately. Over large areas, late-diagenetic reddening has penetrated several tens of meters into the top of the Limburg Group. If a reddened interval of the Limburg Group is covered unconformably by a younger red-bed unit, the exact boundary can be difficult to pick. The base is poorly known because only a few wells in widely separated areas reached it. Towards the London-Brabant Massif, the group rests on the carbonates (frequently silicified) of the Lower Carboniferous Limestone Group (Dinantian). Around the Mid North Sea High, the group grades into an alternation of carbonates and clastics of the Yoredale Formation.

The Limburg group consists of numerous subgroup formations and members. For now we only discuss the ones relevant to the study and mentioned in the previous chapters.

Geul subgroup:
Group of formations, comprising a cyclic succession of predominantly fine-grained siliciclastic deposits devoid of coal seams. In the Northwestern offshore the subgroup locally includes a sandstone-dominated succession.

Epen formation:
This formation is a succession of dark-grey to black mudstones with a few intercalations of grey and buff, (sub-) angular, moderately - to well- sorted, very fine- to medium-grained sandstone. Coal seams are absent, but disperse carbonaceous matter is locally abundant. The interval consists of a number of stacked coarsening-upward sequences (with funnel-shaped GR-log patterns), arranged into several large-scale coarsening-upward trends. The sequences are between 50 and 300 meters thick. Sandstone sheets are intercalated at the tops of some sequences, especially in the upper part of the formation). Shaly mudstones, some containing marine fossils, dominate the basal and middle parts of each sequence. Locally, a black, bituminous, partially silicified and calcareous shale is found at the base of the formation (Geverik Member). In the Northwestern Netherlands offshore and in the adjoining UK sector, the formation is overlain by the Millstone Grit Formation. The boundary has been placed at the base of the lowermost thick sandstone bed of the sandstone-dominated Millstone Grit Millstone Grit succession. It is a diachronous boundary, which becomes younger from North to South. Therefore these formations are also partial lateral equivalents. The base of this formation has been penetrated by only a few wells. Along the Northern margin of the London-Brabant Massif, a basal bituminous shale (Geverik Member) rests on the carbonates of the Carboniferous Limestone Group (Dinantian). The boundary has been placed at the top of the uppermost carbonate-dominated sequence.

Geverik member:
Interval of dark-grey or black, bituminous, shaly claystones, with abundant intercalated laminae of graded siltstone and very fine-grained sandstone. In the type section, dark-grey to black limestone laminae are intercalated in the basal part. The tops of individual beds are frequently silicified. Tuffaceous bands of cm- to mm-thickness can occur. Because of its high uranium- and thorium-content, the unit stands out prominently on GR-logs (300-500 API units). The ‘hot shales’ pass upwards into the non-bituminous, dark-colored mudstones of the main Epen member. The upper boundary is defined by the disappearance of the bituminous character, reflected by an abrupt upward shift to lower GR-log readings. In the type section a gradual transition can be observed from the limestone-shale alternation of the Carboniferous Limestone Group into the marly basal interval of the Geverik Member. Elsewhere, the member is usually found to rest unconformably on massive Dinantian carbonates.

Methods

Limited data is available for this study, for only 2 wells penetrated Dinantian aged rocks in the Northern onshore Netherlands. And seismic acquisition and processing is usually focused on the gas bearing Rotliegend and shallower levels. Information on Dinantian carbonates is found in literature, analogues and wells from the Southern Netherlands. This chapter describes the methodology used in this study to estimate the prospectivity of the Dinantian carbonates onshore Northern Netherlands. The methods are:

- Seismic interpretation
- Time-depth conversion
- Well correlation
- Literature study on, carbonate production, precipitation and geometries, with a focus on the Dinantian

The program used is Petrel 2011. In the results chapter analogues on Dinantian carbonates are compared with the results from seismic mapping and well correlation. See figure 1 for the available dataset.

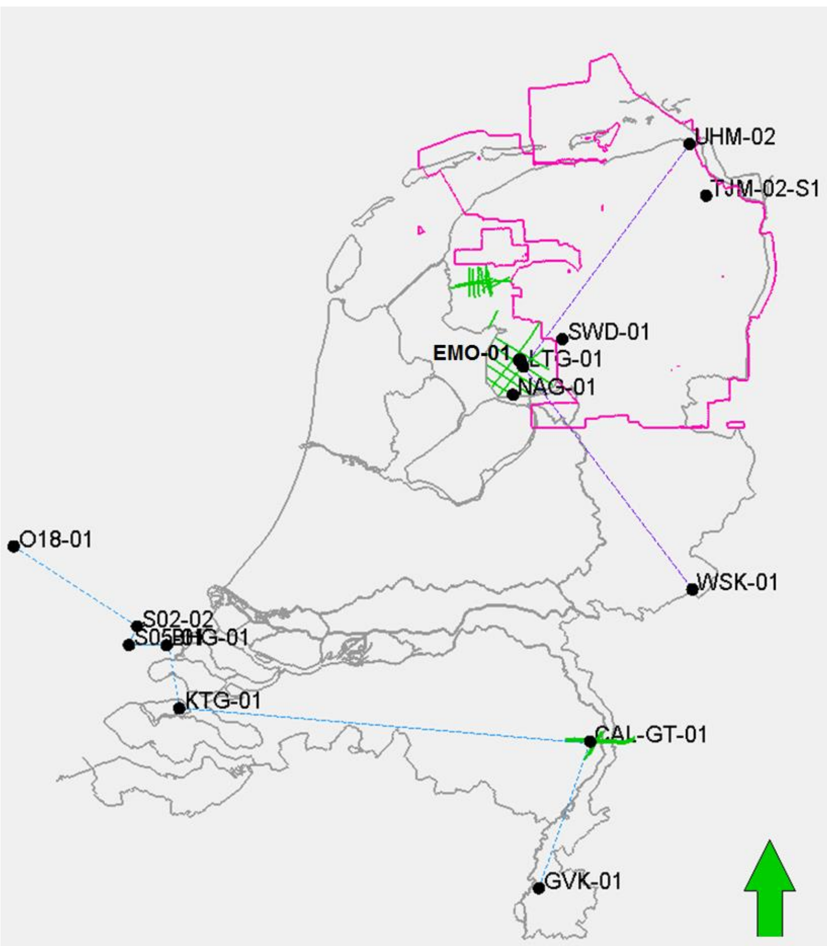


Fig. 1: Outline of the Netherlands with the data used in this study. Pink = outline of the 3D seismic merged Terracube. Green lines = 2D seismic lines in Friesland, Noord-Oost Polder and Limburg, black dots represent the wells and dotted lines are the well sections used for well correlation.

Seismic interpretation

Preceding this study of the Northern onshore, in the Southern onshore region 2 seismic lines have been mapped in Limburg, these lines were shot for locating a new geothermal well: CAL-GT-01 (see figure 1 for the location). the seismic lines and the well data are still confidential, though the interpretations can be found in appendices **III** and **IV**. The Dinantian carbonates have been mapped on a transparent facies clearly present in the seismics. The Limburg area is highly faulted (extension, strike-slip and compaction) and has experienced major uplift. Major karstification features have been found in this Dinantian carbonate succession.

Seismic interpretation was done in the Northern onshore Netherlands, available were 2D seismic lines and a 3D seismic cube. The 2D lines cover the Noord-Oost Polder and Friesland, and were provided by TNO (see figure 1 for location of the data). The 3D seismic comprises several 3D surveys merged into one 3D TerraCube, that covers most of Groningen and the North of Friesland. This merge causes seams between the merges and shows differences in imaging due to differences in the acquisition and processing of the various input surveys. Also the seismic acquisition and processing were focused on the gas bearing Rotliegend and shallower levels. Several areas have limited seismic quality, indicated in figure 2 . Well control is also limited. Only 2 wells penetrated Dinantian aged rocks: UHM-02 and LTG-01 in the Northern onshore region. 4 more wells were used that reached Namurian aged rocks: NAG-01, TJM-02-S1, EMO-01 and SWD-01.

TNO also provided gridlines of a coarse interpretation of Top Dinantian and Top Namurian. Also the gridlines of Top Dinantian made by Kombrink (2008) were made available by TNO. These surfaces together with the well control were used as a guideline for the seismic interpretation in this study.

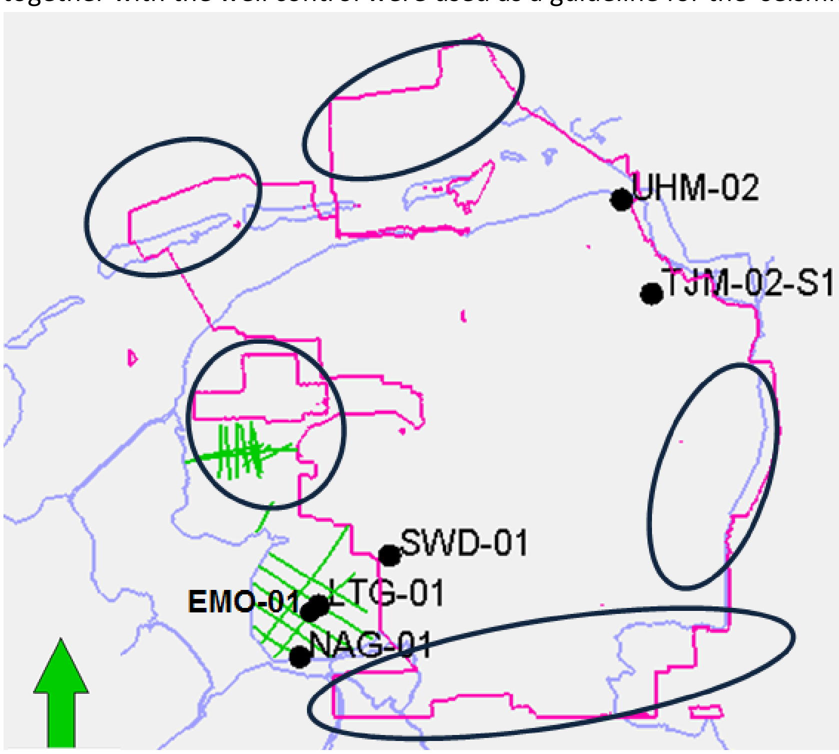


Fig. 2: outline of the seismic data, the black circles represent bad quality seismic data, resulting in larger uncertainties in seismic interpretation

In order to tie the wells to the seismic, depth-time conversion was carried out. Depth-time conversion was done from TVD to TWT, check shots information has been downloaded from the TNO website www. NLOG.nl . Some wells are old and the quality is debatable; the table with information is found below.

wells	age	checkshots	welltops	TD	stratigraphy TD
LTG-01	2004	nlog.nl	matched to synthetics	5162	Banjaard group
UHM-02	2002	nlog.nl	matched to synthetics	5432	Banjaard group
NAG-01	1970	from EMO-01	adjusted by TNO	4303	Epen formation
EMO-01	1969	nlog.nl	adjusted to LTG-01	2547	Epen formation
SWD-01	1966	nlog.nl	disregarded	3649	Epen formation
TJM-02-S1	1972	nlog.nl	adjusted by TNO	6010	Epen formation

Table 1: Information on the wells that were used for seismic interpretation. Check shots for NAG-01 could not be recovered and therefore the check shots from EMO-01 were used for the depth-time conversion. The welltops of EMO-01 differed much from LTG-01, while these wells are just 1 km apart. After log correlation the welltops of EMO-01 were adjusted to the ones of LTG-01. TNO did the interpretation for Top Namurian and adjusted welltops for that purpose to match the seismics, which implies tying the Ubachsbergmember to the seismics. TNO considers the welltops of SWD-01 unreliable. The welltops from TNO have been copied. Welltops for UHM-02 and LTG-01 have been adjusted to the seismics after synthetics were made.

Synthetic seismogram

After depth-time conversion, synthetics were derived from UHM-02 and LTG-01 to tie the welltop Top Dinantian to a reflector in the seismic.
Acoustic impedance of the rock (Z) = the velocity of the rock * the density of the rock.
$Z= v*\rho$
Velocity is v (m/s)
Density is ρ (gr/cm3)

The reflection co-efficient (R) = the acoustic impedance difference between the two rock formations / by the total acoustic impedance of both rock formations, see figure 3.

$$R=\frac{Z_2-Z_1}{Z_2+Z_1}$$

The acoustic impedance is derived from the sonic log (µs/ft) and the density log: RHOB (g/cm3).
The sonic log has the symbol: υ and the unit: micro-seconds per feet (µs/ft).
The density log is called RHOB and has the unit: gram per cubic centimeter (gr/cm3).
That gives an acoustic impedance (Z) = υ*RHOB.
Carbonates overlain by shale deposits, result in a so-called hardkick, see figure 4.

The synthetics for UHM-02 and LTG-01 were created in Petrel2011. They were calculated by the use of a calibrated sonic and density (RHOB) log to create the acoustic impedance log. For the reflection co-efficient the acoustic impedance log is used. Convolution of the reflection log with the wavelet (Butterworth) results in a synthetic seismogram along the wellbore. The result can be found in figure 4 and 5. The Namurian Dinantian transition seems to be carbonates overlain by shale deposits, this results in a so-called hardkick, see figure 4. Results of LTG-01 are debatable for pinpointing the reflector to Top Dinantian because RHOB data is missing at that point, see figure 4.

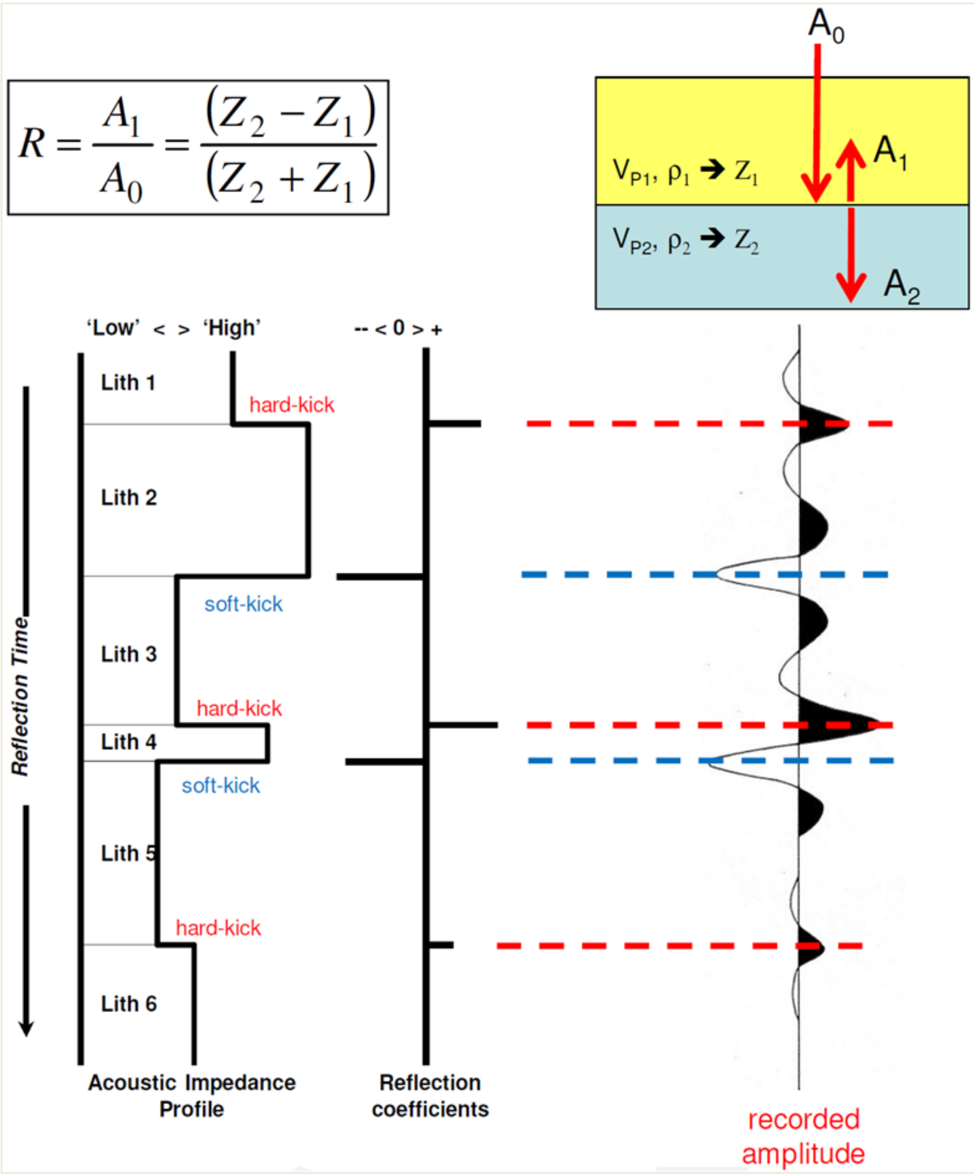


Fig. 3: Reflection co-efficient between rock layer 1: Z_1 and rock layer 2: Z_2. Please note that in this study a hardkick is represented by a negative amplitude instead of a positiv). From Beekman (2012)

This result agrees with the findings of Böker et al. (2012) who interpreted the Dinantian section in the Winterton High area: "Synthetic seismograms for O81-01 and P16-01 were created, based on Ricker Wavelet and acoustic impedance from Sonic logs (no density used because no RHOB log is present for O18-01). Well tops render Top Dinantian as a negative amplitude (hard kick: carbonates overlain by clastics)."

It can be concluded that Top Dinantian represents a hard kick (increase in acoustic impedance); which in this study is represented as a negative amplitude, showcased in blue. Interpretation will be on that blue reflector. Synthetics have not been made by Kombrink (2008), because he had no access to the UHM-02 well data.

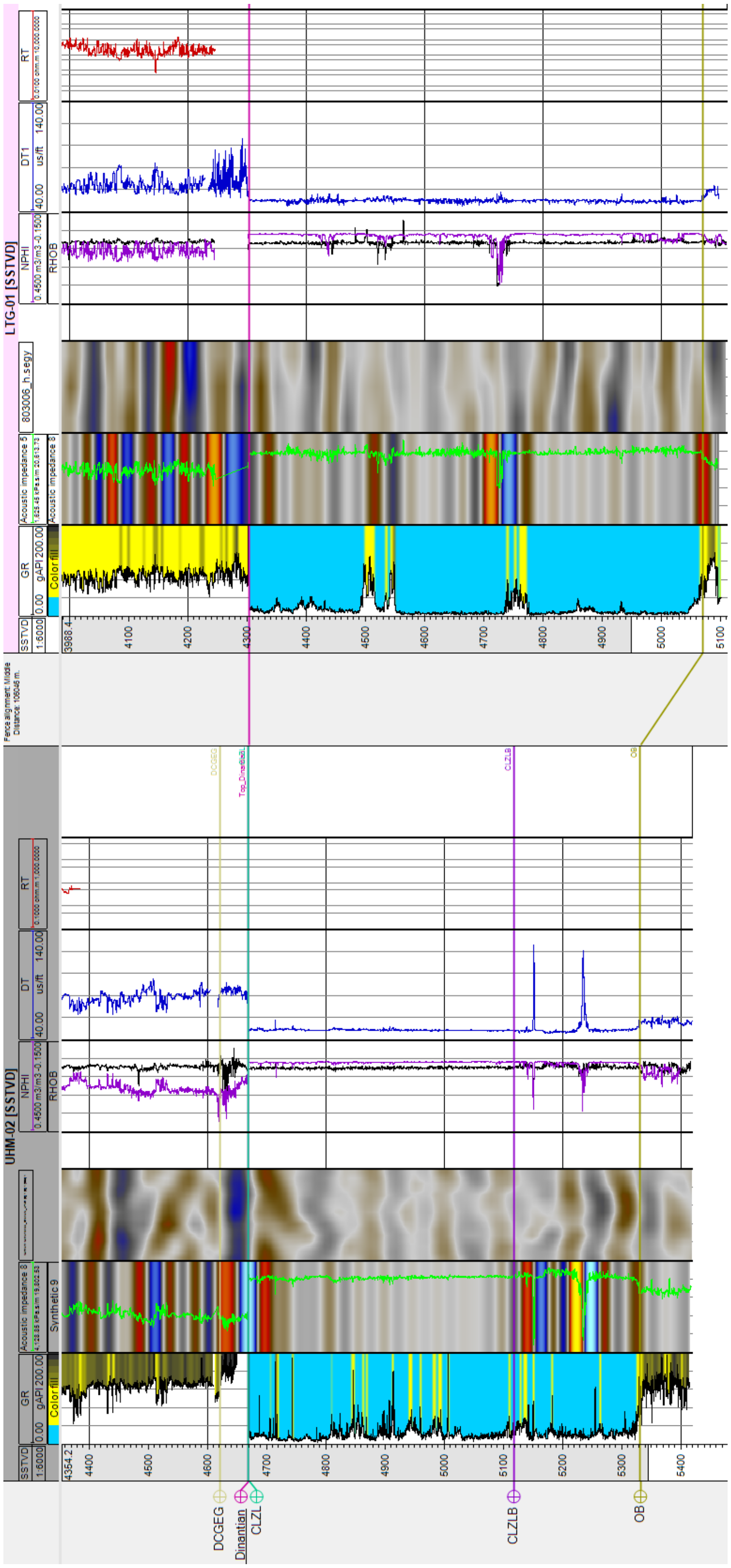


Fig. 4: Gamma-ray log, synthetic log, seismic log, density & neutron log and sonic log. Well top correlated to the strong blue reflector (negative amplitude/hard kick).

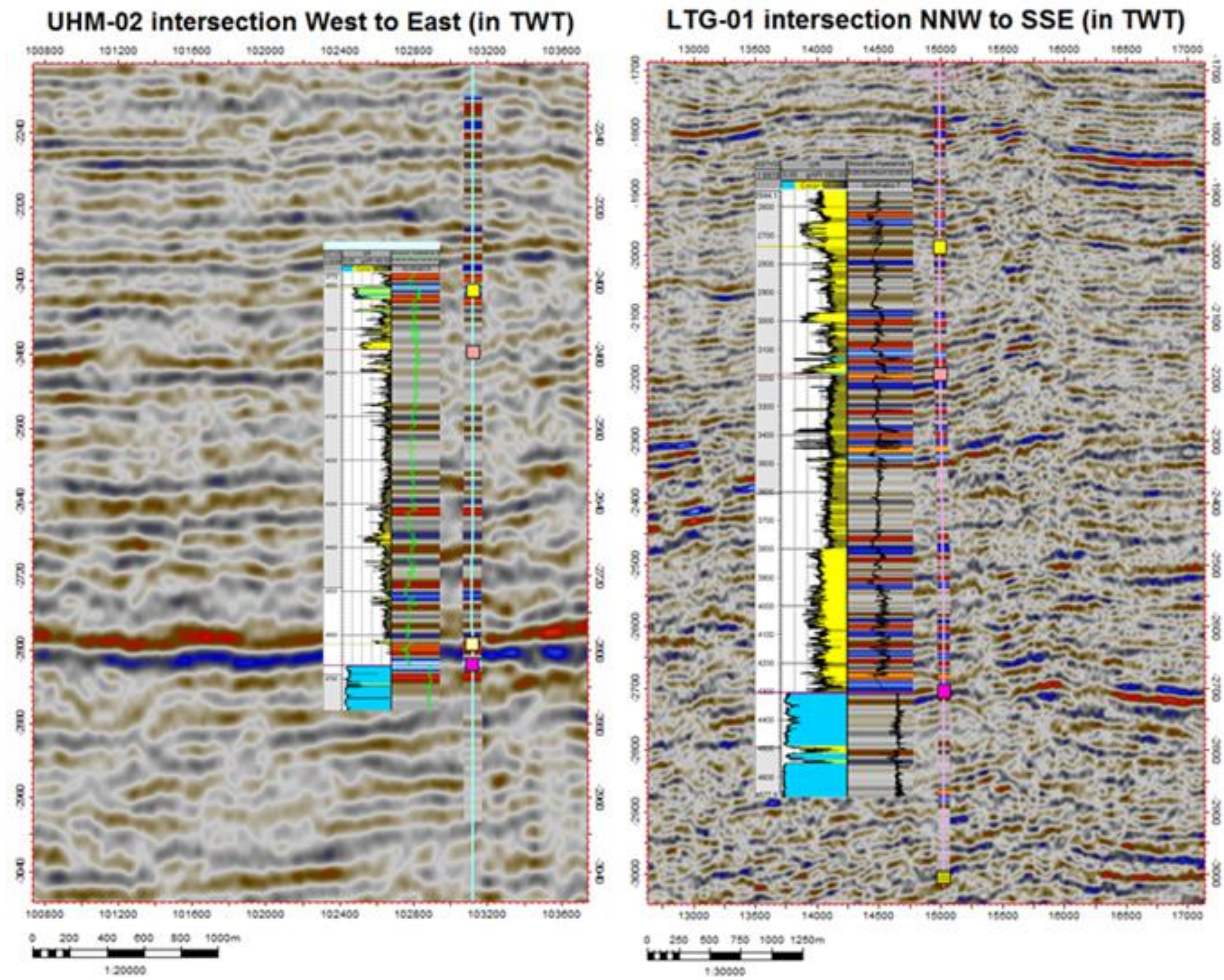


Fig. 5: seismic section through the wells UHM-02 and LTG-01, a hardkick, negative amplitude represents Top Dinantian.

The synthetics are the starting point for seismic mapping of the Top Dinantian carbonates. Defining carbonate build-ups in seismics is not a straight forward process. Schlager (2005. And references therein) states the following: “Seismics resolution tends to overlook small carbonate build-ups and, in other circumstances, non-carbonate build-up deposits and the actual carbonate build-up are visually merged together in a lower resolution seismic image. Living parts of carbonate build-ups are small by seismic standards, easily destroyed and quickly buried by their own debris. The diagnostic criteria for identification of carbonate build-ups in outcrops are far below normal seismic resolution. The seismic tool reveals carbonate build-ups only where many generations of carbonate build-up growth were stacked to thicknesses of tens to hundreds of meters. Where the sites of carbonate build-up growth shift laterally, carbonate build-ups do not stack to seismically recognizable structures but form small lenses embedded in detrital sediment. These small constructions are readily recognized in the field but remain largely hidden in standard seismic data. Equally important are situations where the seismic tool shows more carbonate build-up than is actually there in a stratigraphic or ecologic sense. In addition, sand shoals interfingering with carbonate build-ups may be included in the seismic carbonate build-up unit, see figure 6.”

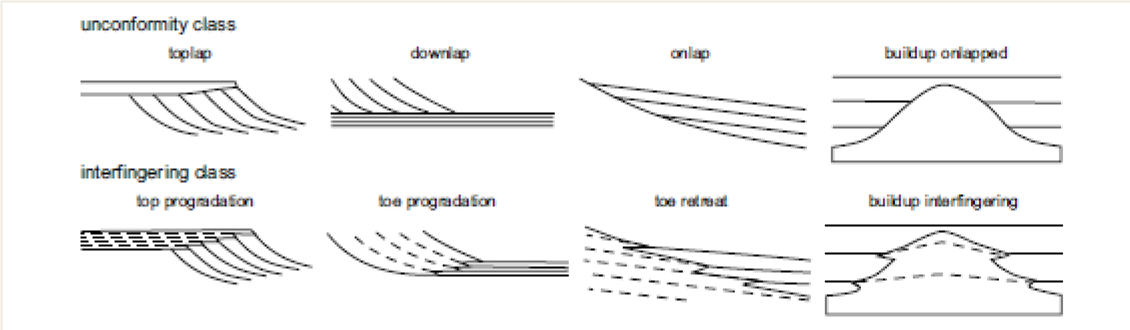


Fig. 6: Depositional geometries of carbonate build-ups where genuine unconformities and pseudo-unconformities caused by facies interfingering may be difficult to distinguish in seismics. From Schlager (2005).

Keeping the foregoing in mind, it is safe to say that the seismic image of the Top Dinantian in the studied platforms might not only comprise carbonate build-ups, it may also include time equivalent basinal clastic deposits. Interpretation still was made by onlapping features (see figure 7). Please note that facies change or interfingering also shows in the seismic. It makes interpretation a lot harder, for the reflectivity of the seismics changes, for instance from blue to red; a hardkick might change into a soft kick when shales are overlain by shales

UHM-02 and LTG-01 are confirmed as carbonate build-ups by the well data and manual interpretation starts there. Seismic quality around UHM-02 is best and interpretation has been started by inline/crossline interpretation with a density of 50 lines by 50 lines. Denser interpretation was made at interesting areas, e.g. where a new carbonate build-up has been found (see figure 8 and 9). After that random (incl. circular) lines were interpreted to ensure lateral consistency of the interpretation.

Large regional faults with offset in the Dinantian have been identified and mapped as well.

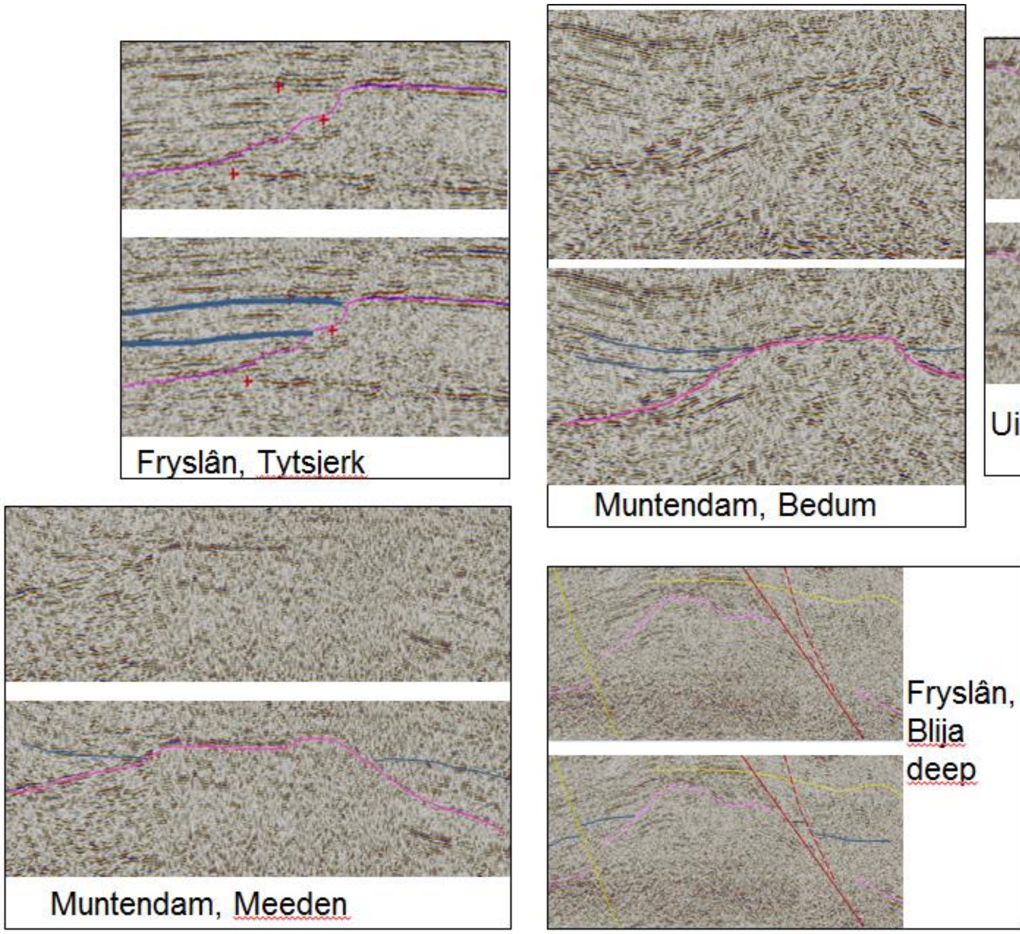


Fig. 7: Onlapping features on which seismic interpretation was done. Yellow represents Top Namurian and the pink horizon represents Top Dinantian. Blue are the identified onlapping features.

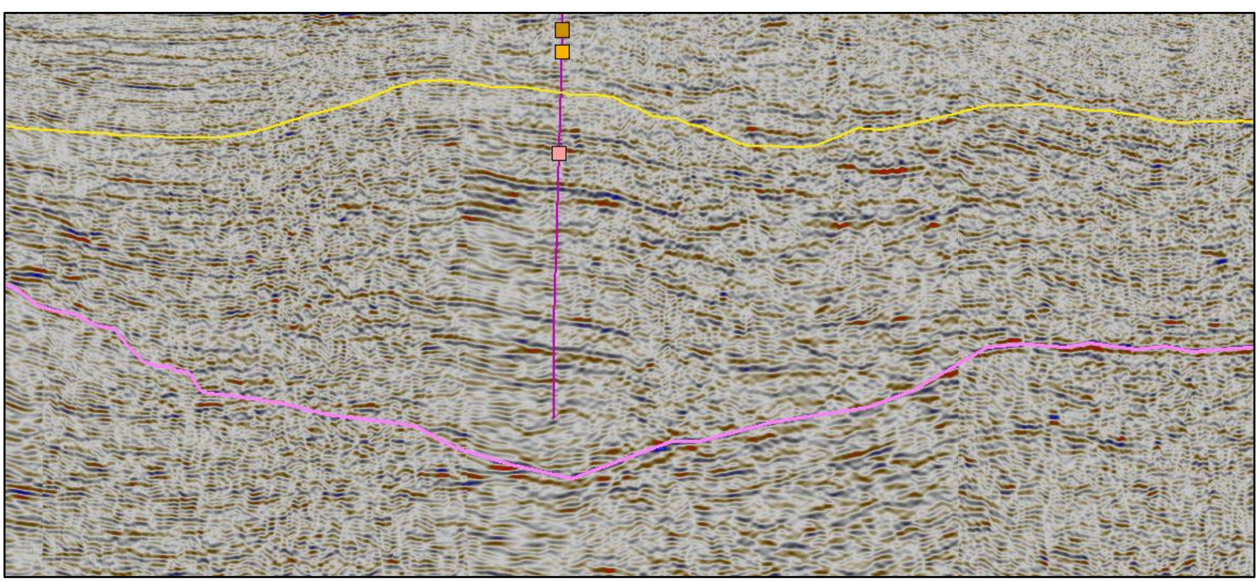


Fig. 8: TJM-02-S1 is situated between two high's as is seen on inline 24634. The Muntendam carbonate build-up can be identified. Yellow represents Top Namurian and the pink horizon represents Top Dinantian.

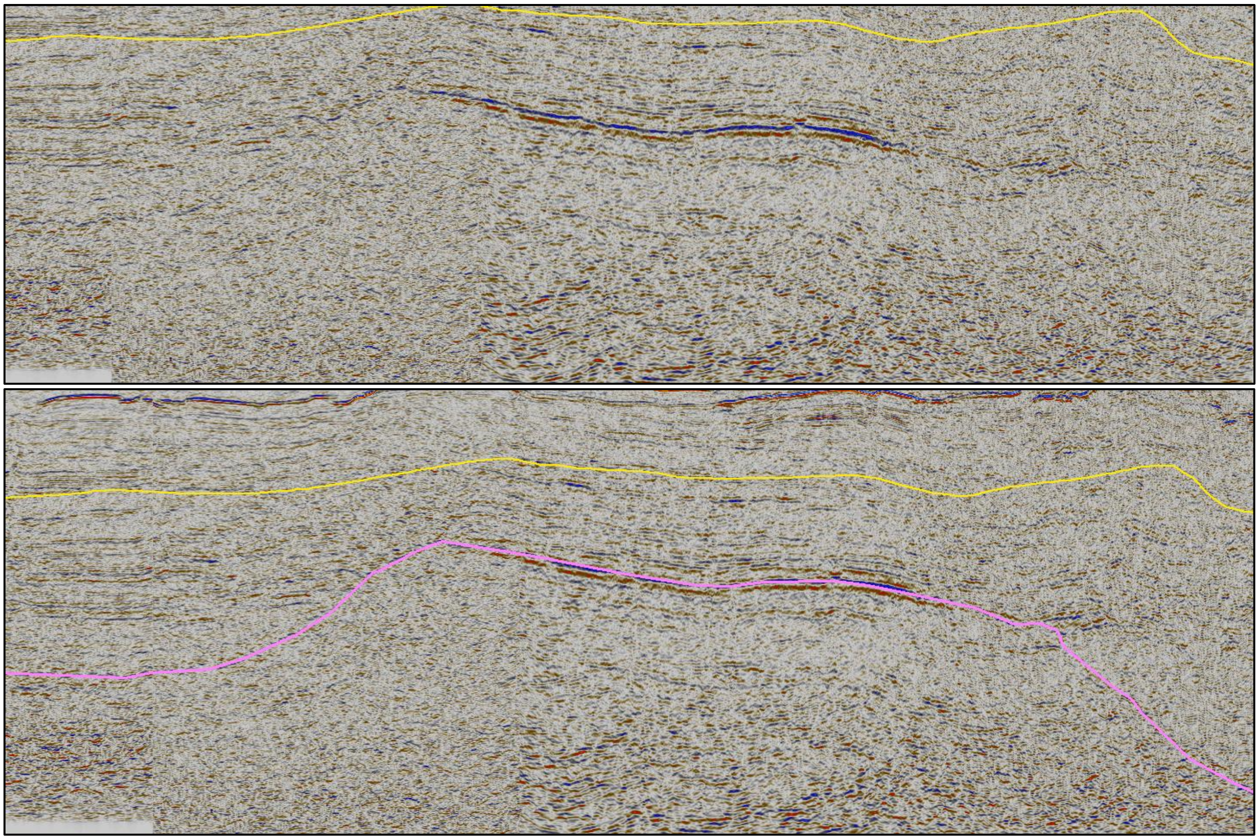


Fig. 9: The Fryslân carbonate build-up is identified at crossline 9806: Yellow represents Top Namurian and the pink horizon represents Top Dinantian.

Time-depth conversion

After the horizon Top Dinantian had been mapped and faults with Dinantian offset had been indicated, a surface in TWT (ms) was created in Petrel2011. The surface was smoothed to filter out small artifacts. Subsequently, time-depth conversion was performed using the velocity model derived from the VelMod 2 project (Dalfsen et al., 2007). Two separate depth models were created, one for the Namurian and one for the Dinantian.

Top Namurian was converted as follows:
A V0 map was created in Petrel2011, by the use of well data (sonic logs). Only 4 wells penetrated The Namurian succession: TJM-02-S1, LTG-01, NAG-01 and UHM-02. The V0 map derived correlates with the thickness of the Namurian, the thicker the Namurian sequence, the higher the initial velocity (V0). Bulls eyes are not recorded near the wells, see figure 1. The function used for the time-depth conversion is V=V0+K*Z, where V0 represents the created V0 grid and k is a constant deducted from Dalfsen et al. (2007) = -0.273. The top Carboniferous has been used as a datum from where the time-depth conversion started. The residuals of this time-depth conversion can be found in table 1.

Top Dinantian was converted as follows:
An interval velocity was calculated manualy by the use of well checkshotdata of wells: UHM-02 and LTG-01. These result of these calculations can be found in table 2 and 3. A mean constant interval velocity of 4306 m/s was used in Petrel2011 for the time-depth conversion function; V=Vinterval. The Top Namurian has been used as a datum from where time-depth conversion started. The residuals of this time-depth conversion can be found in table 4.

	Well	**Residual**
Top Namurian	TJM-02-S1	0 m
	LTG-01	0 m
	NAG-01	0 m
	UHM-02	0 m

Table 1: Residual table for make V0 map and keep K (-0.273; after Dalfsen et al. 2007).

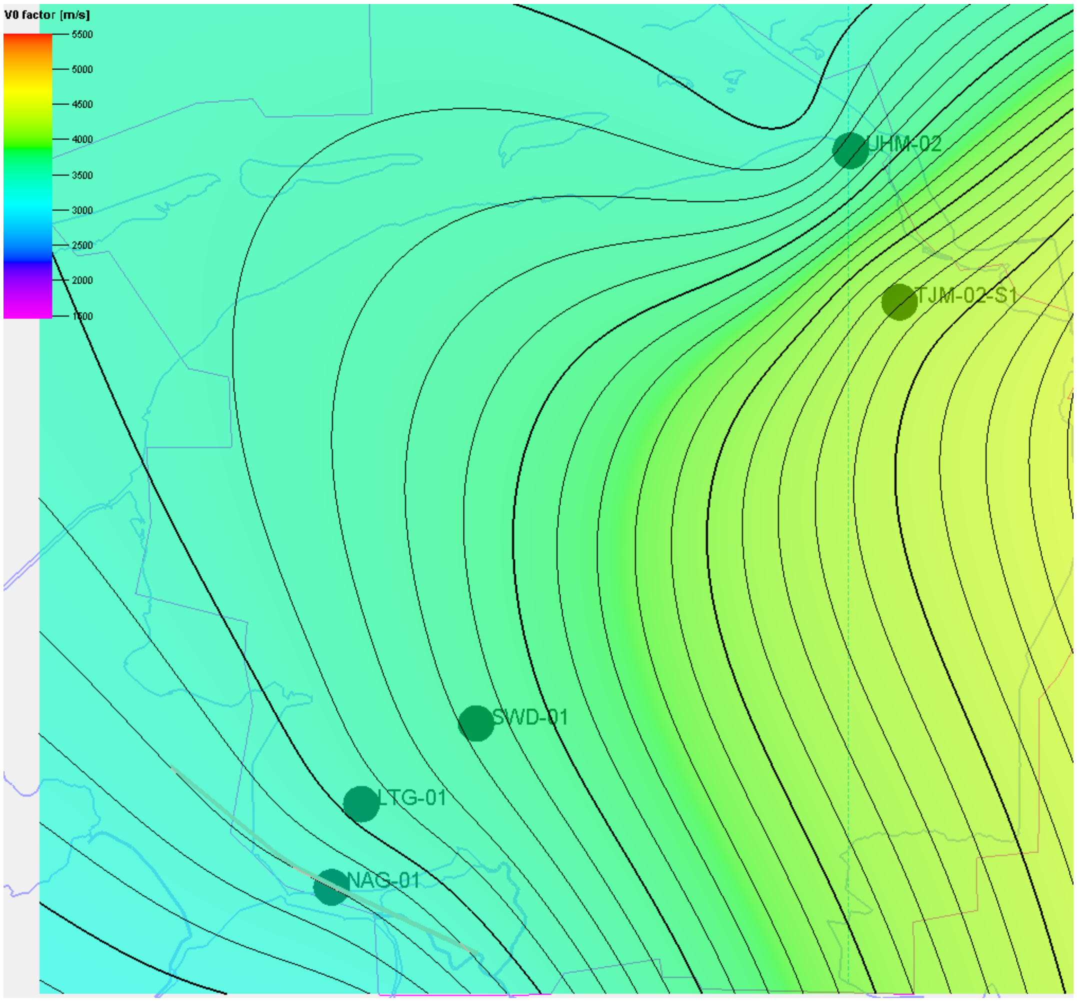


Fig. 1: V0 map produced by Petrel during time-depth conversion. V0 changes with different thickness of Namurian.

UHM-02	**MD (m)**	**TVD (m)**	**thickness (m)**	**TWT (ms)**	**OWT (s)**	**Delta OWT (s)**	**Vint (m/s)**
Base Zechstein	2881	2871	nvt	1954	0,977	nvt	nvt
Base Rotliegend	3170	3157	286	2107	1,0535	0,0765	3739
Top Namurian Ubachsbergmember	3816	3803	646	2410	1,205	0,1515	4264
Top Dinantian	4682	4669	866	2816	1,408	0,203	4266

Table 2:Calculation of interval velocity in UHM-02.

LTG-01	**MD (m)**	**TVD (m)**	**Thickness (m)**	**TWT (ms)**	**OWT (s)**	**Delta OWT (s)**	**Vint (m/s)**
Top Carboniferous	1776	1726	nvt	1473	0,7365	nvt	nvt
Top Namurian Ubachsbergmember	3022	2972	1246	2094	1,047	0,3105	4013
Top Dinantian	4355	4303	1331	2704	1,352	0,305	4364

Table 3:Calculation of interval velocity in LTG-01.

Interval velocity LTG-01 4346 m/s
Interval velocity UHM-02 4266 m/s

Mean interval velocity 4306 m/s

	Well	Residual
Top Namurian	TJM-02-S1	0 m
	LTG-01	0 m
	NAG-01	0 m
	UHM-02	0 m
Top Dinantian	LTG-01	-66,36 m
	UHM-02	-37,15 m

Table 4: Residual table for: Namurian and Dinantian. For Top Namurian the function used is; make V0 keep k (-0.273 Dalfsen et al., 2007). For Top Dinantian the function used is; Velocity interval grid of 4306 m/s.

The residuals for the wells UHM-02 and LTG-01 of Top Dinantian, after the time-depth conversion is:
LTG-01 -66/4303*100=-1.5%
UHM-02 -37/4669*100=-0.8%
These percentages remain well within the uncertainty range, with the limited data available, the little well control and the great burial depths. This surface will be discussed in the results chapter.

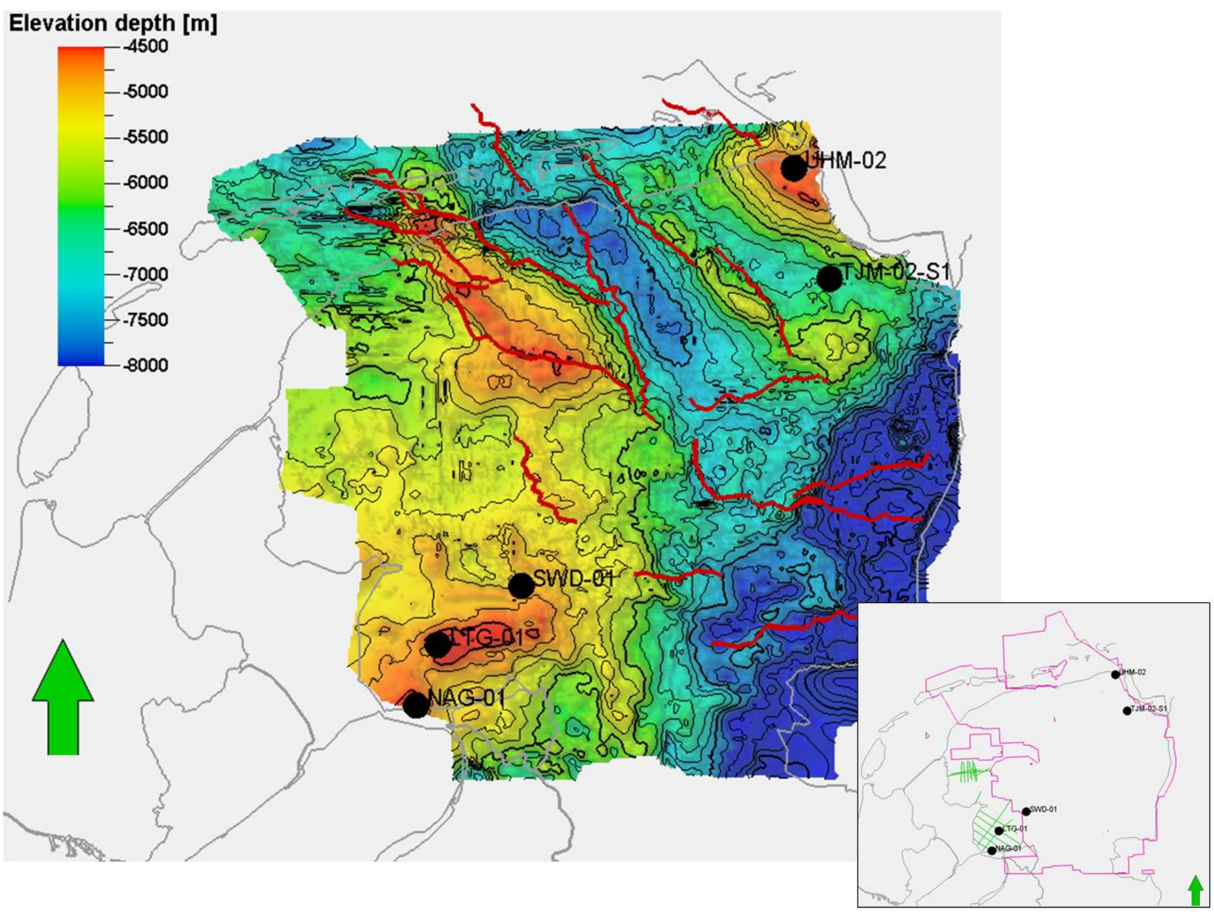


Fig. 2: Depth surface of Top Dinantian after time-depth conversion as described above.

Well correlation

Although well control in the study area is limited. Well correlation has been carried out. Two well correlation panels have been made: a South section and a North section (see figure 1) in order to compare Dinantian log response in both carbonate successions. The used log information comprise: gamma-ray (0-450 gAPI), neutron (0,45- -0,15 m^3/m^3) density (1-2 gr/cm^3), sonic (40-140 µs/ft) and resistivity (0- 10^8 Ωm). The result of these well correlation panels can be found in the results chapter and in appendix **I**.

The gamma-ray log measures the natural background radiation of the formation. Radiation is mainly emitted by potassium (K), thorium (Th) and uranium (U) isotopes. The gamma-ray log is used as lithology indicator. Shale deposits have been colored grey and the gAPI is set to 450-100, sand deposits have been colored yellow and gAPI is set to 100-40 and carbonates have been colored blue at an gAPI of 0-40.

The neutron log generate fast neutrons by a combined chemical source (Am-Be) and they collide with the nucleus of atoms in the formation. The collisions slow the neutrons down and they are measured by detectors. The tool measures the concentration of hydrogen in the formation, which is proportional to porosity.

The density log is used next to the neutron log for both use neutrons in their measuring method. The neutrons are used to estimate the density of the formation. This tool is used together with the mudlog to determine lithology. Each lithology has its own density, changes in this pattern could be due to porosity inhibiters such as faults, fractures or diagenesis.

The sonic log records acoustic impulses that are emitted by the logging tool. The waves only propagate through solids and the arrival of an acoustic impulse is presented in a slowness.

The resistivity log says something about the porosity. After determining porosity from the sonic and the neutron and density logs, the Resistivity log determines the conductivity of the fluids in the pore space. Whereas salt is highly conductive and hydrocarbons are highly resistive.

Log information from Betts (2012).

The CAL-GT-01 well is still confidential and has been removed from the well correlation panel in appendix **I**.

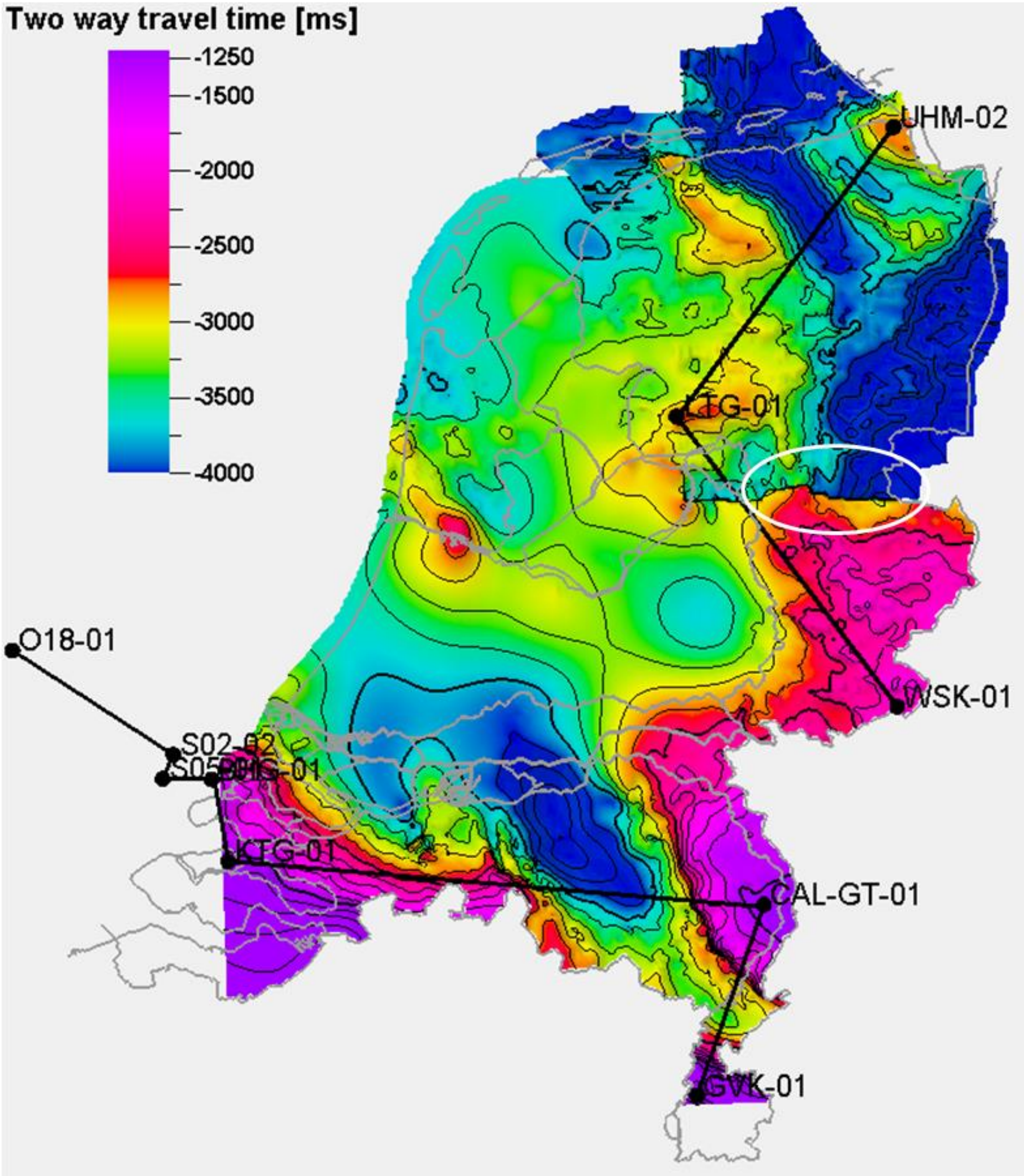


Fig. 1: Outline of the Netherlands, with placing of the wells and placing of the well correlation sections: North and South. The surface represents Top Dinantian in TWT (ms), The Northern onshore part has been mapped in this study, the Southern onshore part has been mapped by TNO (Ed Duin) and represents work in progress. The Northern onshore part comprises of more seismic data compared to the Southern onshore part, therefore the Northern onshore part has been mapped in more detail. The white circle represents an area of limited seismic data, where the uncertainty in interpretation increases.

Carbonate production, precipitation and geometries, with a focus on the Dinantian

Introduction
This chapter summarizes the main features found in carbonate production, precipitation and geometries. It is based primarily on the book: "Carbonate Sedimentology and Sequence Stratigraphy", written by Wolfgang Schlager in 2005.

There are 3 modes of carbonate precipitation proposed:
A *Abiotic* precipitates where biotic effects are negligible. Ooids and precipitation of marine evaporites is an example of an abiotic process.
B *Biotically induced* precipitates in which the organism sets the precipitation process in motion but subsequent organic influence is marginal or absent. The product is very similar, often indistinguishable, from abiotic precipitates.
C *Biotically Controlled* precipitates in which the organism determines location, beginning and end of the process, and commonly also composition and crystallography of the mineral. All skeletal carbonate falls in this category. A subdivision can be made in; C1 controlled precipitates by photo-autotrophic organisms that generate organic matter from dissolved substances, sunlight, and C2 controlled precipitates by heterotrophic organisms that are independent of light but require particulate organic matter for food.

Currently, organisms have the first hand in precipitation in most carbonate settings and abiotic precipitation will kick in if biotic fixation is insufficient. Thus, abiotic precipitation is a sort of "default setting" in the carbonate system of modern oceans (term credit to Ron Perkins).

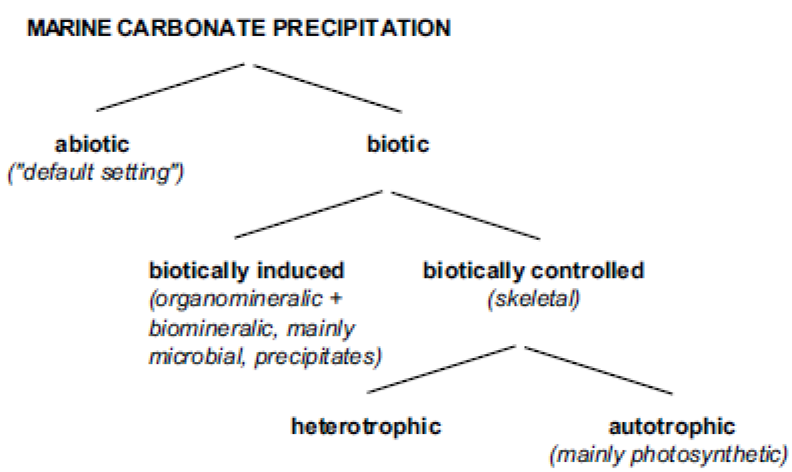


Fig. 1: Pathways of carbonate precipitation in aquatic environments – a cascade of options governed by the degree of biotic influence. From Schlager (2005).

Autotrophic producers	**Heterotrophic producers**
Cyanobacteria (only biotically induced precipitates)	Foraminifera
Coccolithophorid algae (Haptophyceae)	Archaeocyathans
Green algae (such as dasycladaceans, codiaceans)	Sponges (e.g. pharetronids, stromatoporoids, chaetetids)
Red algae	Ahermatypic corals (Scleractinia)
Autotrophic production via symbionts	Most bivalves
Many larger foraminifers	Gastropods
Hermatypic corals (Scleractinia)	Cephalopods
Certain bivalves (Tridacnids, rudists?)	Arthropods (e.g. trilobites, ostracodes, barnacles)
	Brachiopods
	Bryozoans
	Echinoderms

Table 1: Important autotrophic and heterotrophic carbonate producers. (Schlager,2005)

Marine carbonate production nearly always depends on photosynthesis as a starting point. The organisms at the starting point of the food chain are called autotrophs (literally: self-feeders); organisms further down the food chain depend on other organisms for food and are called heterotrophs. The rate of photosynthetic production, the primary productivity, in the marine environment depends on the light intensity and the concentration of dissolved nutrients, such as phosphorous, nitrogen or carbon.

The three precipitation modes cluster into three preferred production systems, or factories, that differ in dominant precipitation mode (figure 2) and mineral composition (figure 3). The factory classification scheme uses the terms tropical (T), cool-water (C)and mud-mound (M) factory (Schlager, 2000, 2003).

T stands for “tropical” and “top-of-the-water-column”. Biotically controlled precipitates dominate. Most abundant among them are photoautotrophic organisms, for instance algae and animals with photosynthetic symbiotic algae, e.g. certain foraminifers and certain mollusks. The other characteristic products are abiotic precipitates like marine cements and ooids. Heterotrophs devoid of symbionts are common, but non-diagnostic contributors. Construction of wave-resistant structures by organic frame building or rapid marine cementation is common, particularly at the shelfslope break. The T factory is restricted to warm, sunlit waters of the ocean that are high in oxygen because of constant equilibration with the atmosphere and low in nutrients because of intensive competition. In modern oceans, the characteristic settings are surface waters between 30° N and 30°S. The Northern and Southern limit of the T factory closely follows the line where the mean temperature of the coldest month is about 20 °C. The T factory may also pass into the cool-water factory moving downward in the water column, for instance at the boundary between the warm surface layer of the ocean and the thermocline. Furthermore, transitions from T to C factory occur in shallow tropical upwelling areas where cool, nutrient-rich water comes to the surface (Schlager, 2005. And references therein).

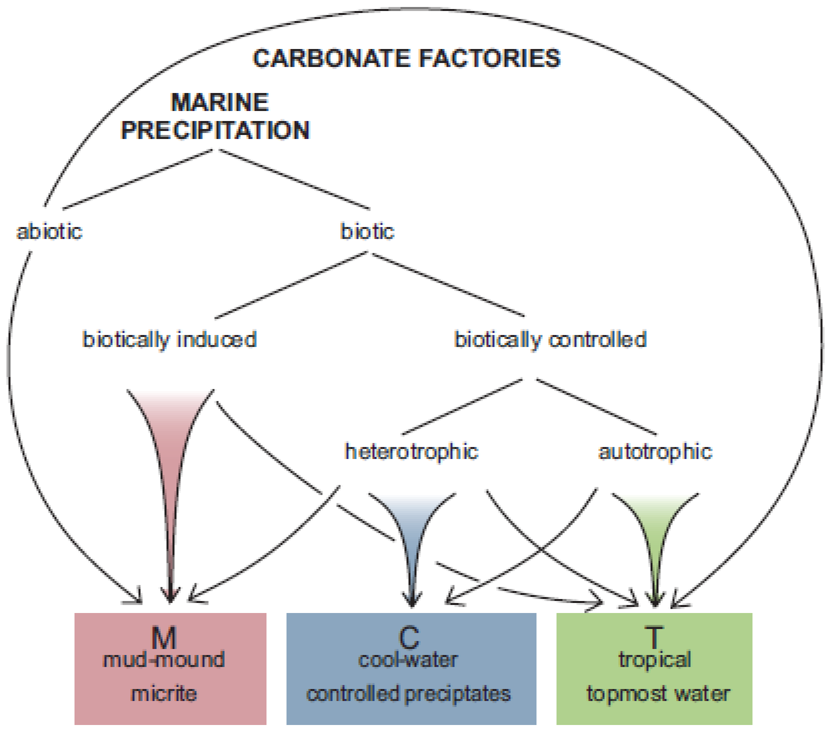


Fig. 2: Precipitation modes (Schlager, 2005).

The letter C is derived from cool-water and controlled precipitation. The products are almost exclusively biotically controlled precipitates. Heterotrophic organisms dominate. The contribution of photoautotrophic organisms in the form of red algae and symbiotic larger foraminifers is sometimes significant. The sediment typically consists of skeletal material of sand-to-granule size. Cool-water carbonates lack shoal-water reefs and oolites; carbonate mud and abiotic marine cements are scarce. The cool-water factory extends pole ward from the limit of the tropical factory (at about 30◦) to polar latitudes. The transition to the T factory is very gradual. The C factory also occurs at low latitudes underneath the thermocline below the warm surface waters and in upwelling areas. Nutrient levels are generally higher than in the tropical factory. These constraints set a wide depth window for the cool-water factory from upper neritic to bathyal and even abyssal depths. The most common setting is the outer neritic, current-swept part of continental shelves. The transition to the T factory normally extends over more than thousand kilometers (Schlager, 2005. And references therein).

The letter M alludes to mud-mound, micrite and microbes. Intensive work in the past 15 years established the significance of this carbonate factory in the Phanerozoic. The characteristic component is fine grained carbonate that precipitated in situ and was firm or hard upon formation. A number of detailed case studies suggest that precipitation of this fine-grained carbonate was caused by a complex interplay of biotic and abiotic reactions with microbes and decaying organic tissue playing a pivotal role (Schlager, 2005. And references therein).

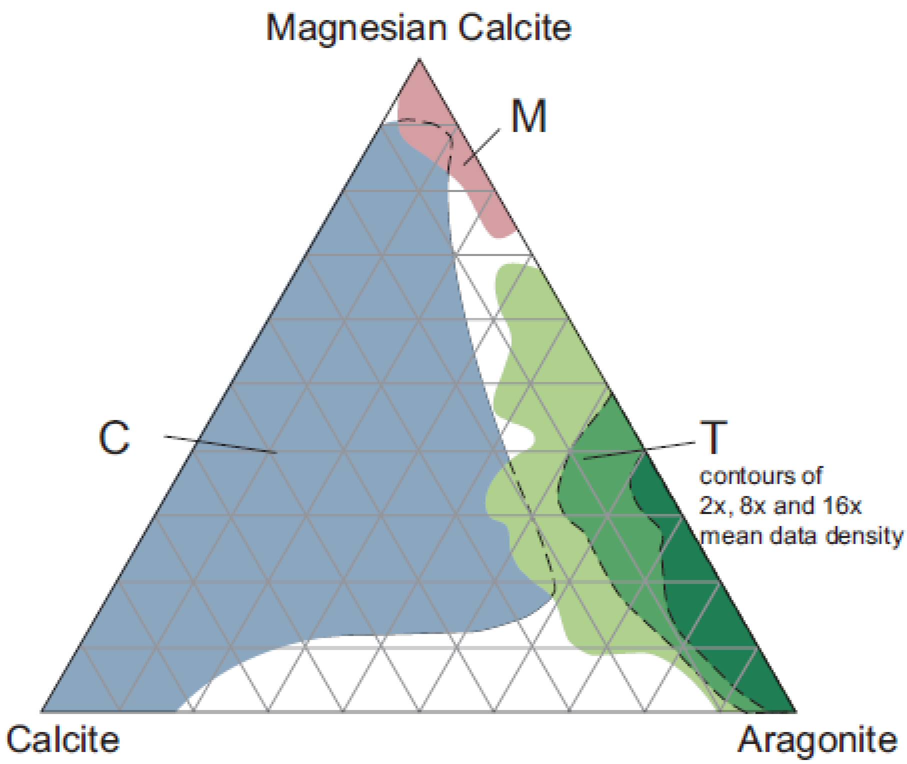


Fig. 3: Mineral composition (Schlager, 2005).

Abiotic marine cement is the second most important product of this factory. It forms typically in vugs (such as *Stromatactis*) within the rigid framework of micrite. Biotically controlled (skeletal) carbonate may occur but is not characteristic. The typical setting of the M factory in the Phanerozoic are aphotic, nutrient-rich waters that are low in oxygen but not anoxic (Schlager, 2005. And references therein). These conditions often prevail in the thermocline, i.e. at intermediate depths below the mixed layer of the sea. However, in the Proterozoic and after severe extinctions in the Phanerozoic, a carbonate production system that was dominated by biotically induced micrite and abiotic marine cements also extended into the shallow environments normally occupied by the T factory. These products are sufficiently similar to the classical M factory to include them here. Textures and structures of the carbonate products do not indicate that the involvement of phototrophic microbes – as opposed to aphotic ones – fundamentally changes the precipitation process of the biotically induced carbonates. At present it is very difficult to distinguish between photically and aphotically formed micrite unless associated sessile skeletal organisms provide the necessary information.

Geometry

The geometry of carbonate deposits results from the spatial patterns of production and the effects of by waves and currents. Four commonly occurring patterns in carbonate geometry are directly related to principles of carbonate production and the hydrodynamics of the water column:

1. "The rich get richer". Carbonate factories tend to build elevated, localized accumulation because biotic and abiotic precipitation operates best where little other sediment disturbs the local environment. Once a production site has risen above the adjacent sea floor, precipitation is

likely to accelerate and build up the accumulation even faster. This effect is felt in a wide range of scales, from decimeter-size stromatolite heads to Bahamian-sized platforms.

2. “The sea is the limit”. Carbonate production is highest in the uppermost part of the water column but the terrestrial environment immediately above is detrimental to carbonates. Consequently, carbonate accumulations tend to build flat-topped platforms close to sea level.
3. “The bucket principle”. The boundary of the platform top shaped by waves and the slope shaped by gravity transport is a significant juncture in all depositional systems. Tropical platforms tend to form a discrete rim at the platform-slope boundary. Several effects contribute to rim construction. The outer edge of the wave-swept platform top is the preferred location of frame builders and thus of barrier reefs that form a rim. The organic reef structures are further strengthened by abiotic cementation that is particularly extensive there because of high primary porosity and the pumping effect of heavy seas. Furthermore, the upper slope environment is a preferred location of microbial crusts and cements that stabilize the foundations of the shoal-water barriers. The production of the platform rim is higher than that of the platform interior such that the rim rises above the lagoon and sheds its excess sediment both downslope and into the lagoon. Cool-water carbonates have no rims to speak of and therefore tend to form seaward sloping profiles in equilibrium with wave action. Accumulations that form below intensive wave action are convex rather than flat-topped.
4. “Steepen the slopes”. Carbonate slopes steepen with height and are generally steeper than slopes of siliciclastic accumulations. Several effects contribute to this trend: Shoal-water carbonate production includes much sand and rubble; these materials cannot be carried far and have high angle of repose. Slope lithification retards slumping and stabilizes steep angles once they are formed.

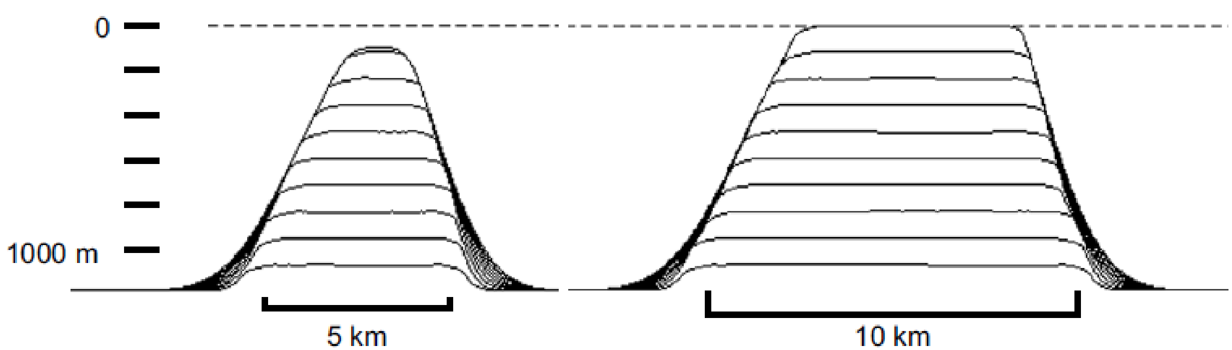


Fig. 4:Effect of increasing slope height on two atolls of different size. Carbonate production of both atolls starts in the area marked by black bars. Both atolls first aggrade, then retrograde as slopes get higher. Retrogradation reduces the production area at the top and leads to gradual drowning. Time of drowning depends on the size of the production area. After 400 ky, the large atoll still is healthy and its flat top built to sea level. The small atoll is virtually dead. Its top lies 100 m below sea level where production is so low that it no longer compensates for sediment loss by downslope transport – aggradation ceases and the flat top changes into a convex structure: a mound. From Schlager (2005).

Schlager classifies 5 main types of carbonate build-ups: reef, ramp, mound, platform and platform rim.

Reef
In carbonate sedimentology, the term reef denotes a wave-resistant buildup formed by the interplay of organic frame building, erosion, sedimentation and cementation (Wright and Burchette, 1996).

Ramp
Ramps are shoal-water carbonate systems that lack the steep slope seaward , they typically show a seaward-sloping surface with dips of 0.1° - 1.5°. Ramps were depicted as systems devoid of an offshore rim (Ahr, 1973). Ramps lack the high energy belt, that rimmed platforms form off shore.

Mound
James and Bourque (1992) divide organic carbonate buildups into reefs and mounds. In this classification, “mound” denotes a rounded, hill-like, submarine structure composed of skeletal material or micrite of predominantly microbial origin. Mounded accumulations of skeletal material can be interpreted as hydrodynamic structures just like any other detrital accumulation. Carbonate mud mounds are isometric or elongate submarine hills. Their top is normally convex and lacks the horizontal surface of carbonate platforms or of reefs built to sea level. Like reefs, mud mounds (with the exception of Waulsortian mounds) commonly show a core flanked by debris aprons that steepen with the height of the mound and sometime dip at over 40◦ (Lees and Miller, 1995). In contrast to reefs, the top of the mound normally does not prograde; only the base of slope progrades to the degree required by the increase in height of the mound. The convex top of the mounds probably reflects their formation in deeper water below the “shaving” effect of wave action. Where mounds build into the zone of intensive wave action, their top flattens and their facies changes. Conversely, the geometry of slowly drowning reefs may gradually change from flat platform to mound as they subside below wave action (Schlager, 2005. And references therein).

Platform
Carbonate platform is a widely used and rather loose term. The dictionary definition precisely captures the essence of the usage of this term in carbonate sedimentology: “a horizontal flat surface usually higher than the adjoining area”. Shoal-water carbonates form flatter tops than other depositional systems because (1) the high-production zone is abruptly limited by sea level, (2)waves and currents efficiently redistribute sediment from high-production areas to fill up depressions, and (3) the platform margin tends to develop a wave-resistant rim that protects the sediment of the platform interior. Size is not a rigid criterion for defining carbonate platforms. However, the term is usually applied to features that are kilometers to hundreds of kilometers across and rise many tens of meters to thousands of meters above the adjacent basin floor. Carbonate platforms may be attached to a land mass or detached, isolated features that are surrounded by deeper water on all sides. Platforms may prograde, aggrade vertically, or retrograde.

Platform rim.
During most of the Phanerozoic, shoal-water carbonate systems were able to build rims in the zone of perennial wave action. Currently, some reef communities can build into the intertidal zone even in settings that face the full power of oceanic waves in the trade-wind belt. The system can build into the supratidal zone by forming “islands” of storm ridges that may contain freshwater lenses and be capped by terrestrial (carbonate) eolianites. The platform rim need not be a reef. Carbonate sand shoals can

A summary of all these geometries can be found in table 2.

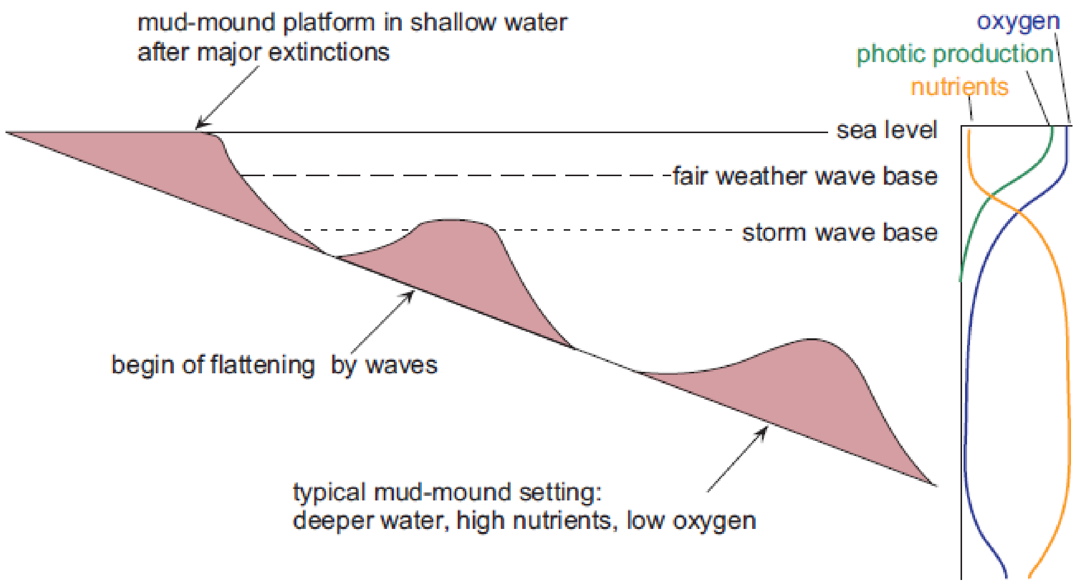


Fig. 5: Environmental setting of the marine M factory. The factory is best developed in the nutrient-rich waters of the thermocline but may extend into the zone of wave action if the T factory is weak. Below the zone of wave action, accumulations usually are mounds; in the zone of wave action they become flat-topped platforms. From Schlager (2005).

form wave-resistant barriers at the platform margin. They may consist of oolites, precipitated locally in the mixing zone of normal marine and platform waters, or of skeletal debris fromthe outer, winnowed parts of the platform. Either type can build into the supratidal zone and is prone to early lithification in the submarine or the supratidal environment. This early lithification greatly enhances the wave resistance of the shoal and reduces the rate of lateral migration to almost zero. Consequently, the hydrodynamic effect of these shoals is similar to that of reefs and reef aprons, both are wave-resistant, stationary structures near the platform margin. The efficiency of reefs and shoals as barriers against wave energy depends on the elevation of the crest and the continuity of the rim. A geometric criterion for elevation into the zone of wave action is the presence of a flat top.

Geometry	Precipitation in	appearance	Sequence
Platform	Shallow water	Flat top, with rim	Progradation
Mound	Deep water	Convex, microbial origin	No progradation
Ramp	Shallow water	~1,5° slope	No progradation
Reef	Shallow water	Forms a framework	No progradation

Table 2: Summary of the geometries present in carbonate build-ups. Please note that a mound geometrie can tranform into a platform geometry when relative sealevel lowers. And a platform geometry can transform into a moun geometry when relative sealevel rises.

The three carbonate factories differ not only in the pathways of precipitation but also through the geometry of their deposits. The main points are discussed in more detail below.

T factory

When left to its internal dynamics, the T factory will strive towards a platform shape, i.e. a flat top near sea level and a steep slope on the seaward side; only minuscule parts of the system will extend into the terrestrial environment. A critical element in the carbonate edifice is a wave-resistant rim at the boundary of the wave-swept top and the slope shaped by gravity transport – hence the term “rimmed platforms”. The presence of a rim, often built to sea level, disrupts the seaward sloping surface normally developed by loose sediment accumulations on a shelf. The growth anatomy of a rimmed platform is that of a bucket: a competent, rigid rim protects the loose sediment accumulation of the platform interior. Platform morphologies are common with the T-factory but they are not diagnostic. If the T factory is weak, the M factory may occupy the niche and build platforms with flat tops (and rims) at sea level (figure 5).

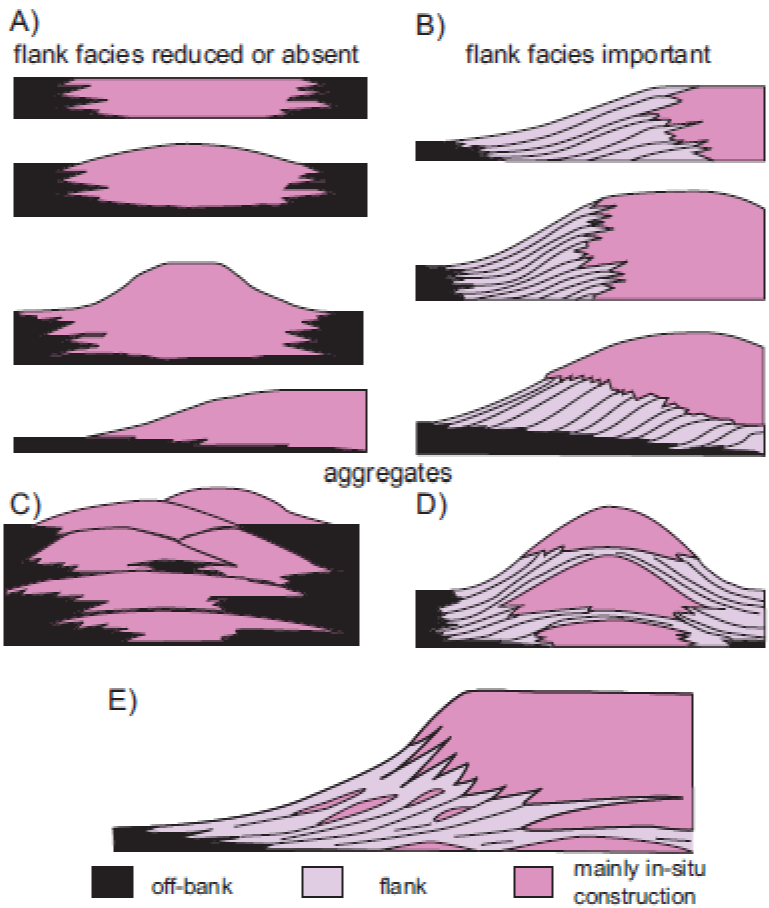


Fig. 6: The M factory typically produces upward-convex accumulations, the mounds, that interfinger laterally with the surrounding facies. Flank facies are present when the factory sheds much debris. (Schlager, 2005)

C factory

Modern cool water carbonates essentially lack the ability to build rims. Consequently, their characteristic depositional geometry is that of a ramp. Many cool water accumulations lie in zones of strong winds and high wave energy. Consequently, accumulation in the shallow part of the ramp may be low.

Fig. 7: Paleozoic mud mounds in the Algerian Sahara that formed on a ramp in an epeiric sea. The exquisitely preserved mounds in this photo are tens of meters high and over hundreds of meters in diameter. The rounded tops as well as biota and sediment facies suggest that even the crests lay below wave base. Photo by B. Kaufmann (Schlager, 2005)

M Factory

The favorite setting for accumulations of the mud mound factory are deeper water environments in the thermocline with low lateral influx of sediment. When left to its own dynamics in this setting, the M factory will produce mounds, i.e. circular or elliptical, upward-convex accumulations that rise above the adjacent sea floor (figures 6 and 7). What sets these mounds apart from purely mechanical accumulations of muddy sediment is the abundant evidence of syndepositional lithification of the structure. This evidence consists primarily of microborings, cracks and large cavities filled by coeval sediment and clasts of micrite, the so-called clotted micrite. Additional arguments for pervasive lithification of the mound edifice are the steep dip (commonly 40-50◦) of the micritic flank deposits (Lees and Miller, 1995) and fractures filled by coeval sediment in micrite deposits. The M factory has no monopoly on mound geometries even though they are very common in this factory. Algal mounds of the T factory (Roberts et al., 1988) and bryozoan mounds of the C factory (James et al., 2000) illustrate that the mound geometry is not diagnostic of a single factory.

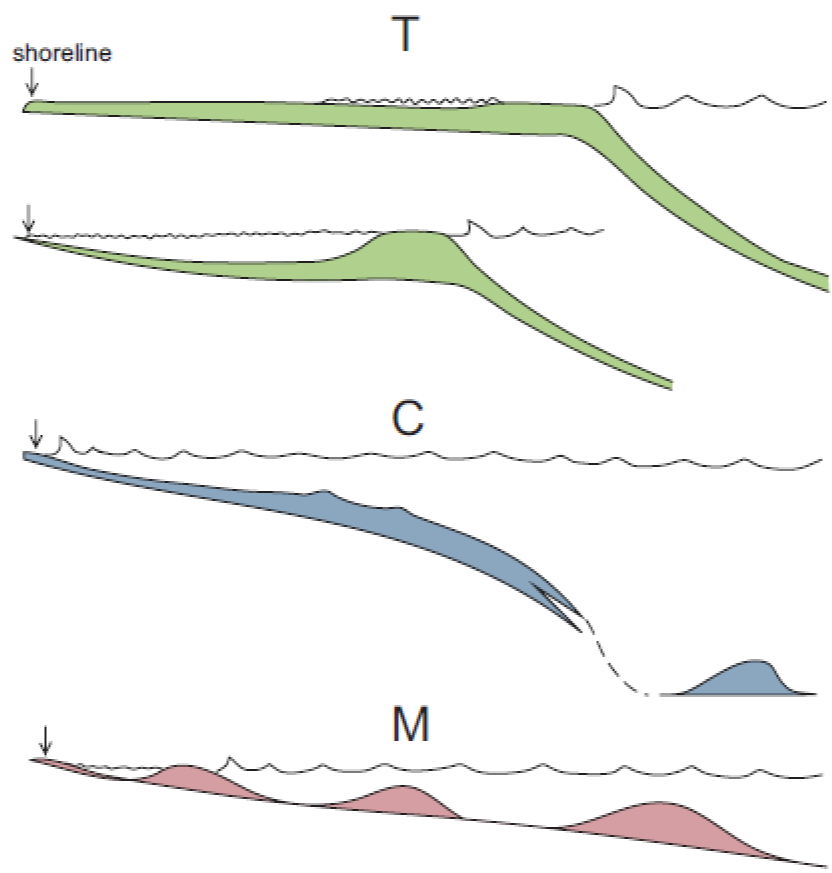


Fig. 8: Cartoons of the depositional geometries of the three carbonate factories. The cross sections show sea level and wave patterns, bottom morphology and thickness variation of a typical growth increment. The arrow marks the shoreline. T factory (green) produces platforms rimmed by reefs or sand shoals; the factory exports much sediment of all grain sizes; consequently, slopes are steep and rich in shoal-water debris. C factory (blue) cannot build shallow offshore rims, only scattered deeper-water skeletal mounds. The geometry of the accumulations is that of a ramp with the highest energy conditions close to shore. M factory (red) forms convex mounds on gentle slopes below the zone of wave action. The mounds develop flat tops and caps of grainstones where they build into the zone of intense wave action. The flanks of mounds may be steeper than the maximum angle of repose of sand (about 40◦) because micrite cements can stabilize the flanks. (Schlager, 2005)

Dinantian Carbonate precipitation

This section will go into the specifics of the carbonate precipitation for carbonate production in the Dinantian era differs significantly from the rest of the Phanerozoic. Buggisch (1991) postulated that the stratigraphic record clearly shows a mass extinction after the late Frasnian. Throughout the whole world, Devonian-Carboniferous buildup communities take the form of carbonate mud-mounds and rarely cluster reefs. Fully formed major framework reefs did not occur again until the Permian. This excludes the geometry "reef" as described by Schlager (2005) to have formed during the Dinantian.

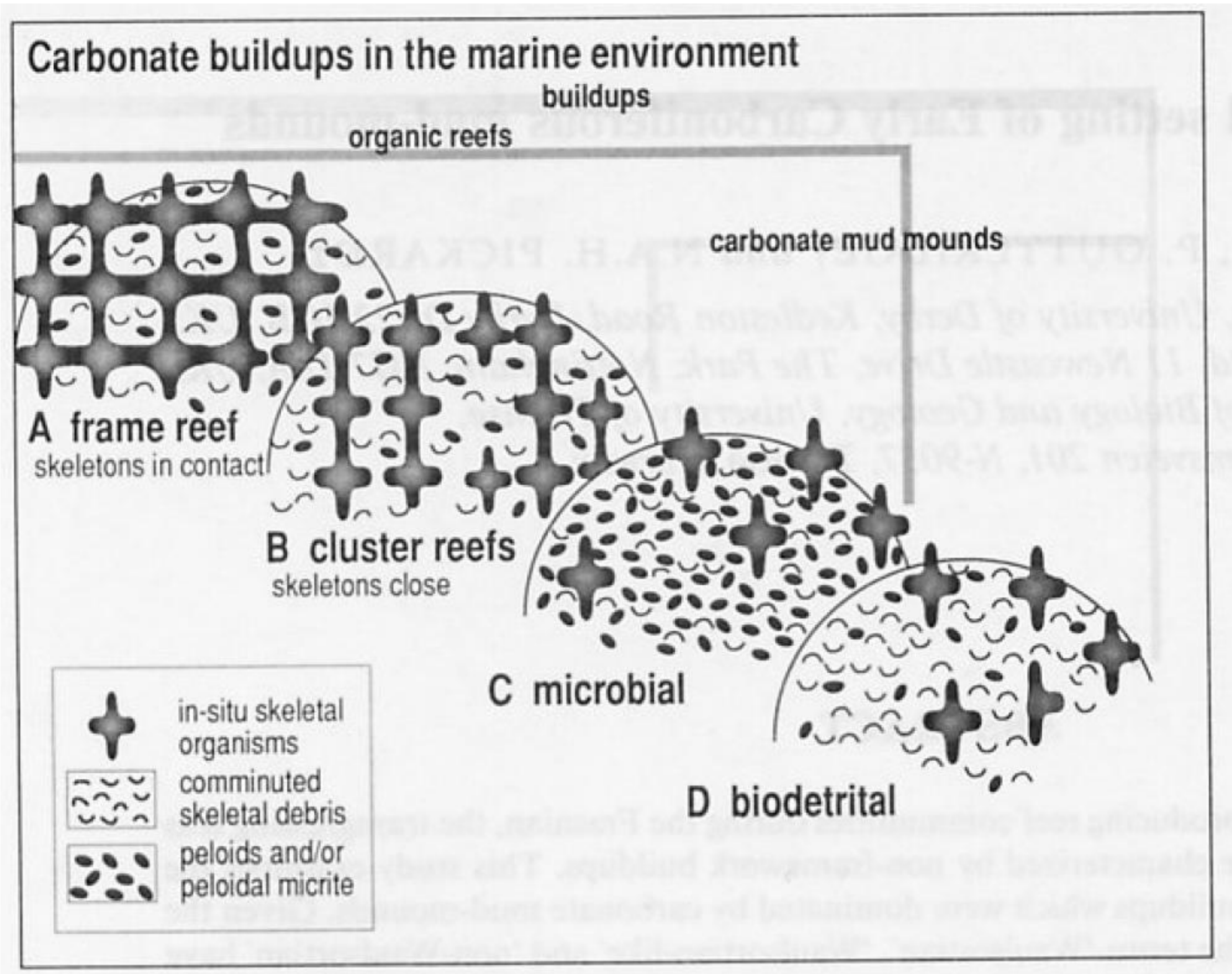


Fig. 9: The principal types of carbonate build-up in the marine environment. In category B the skeletal forms are locally juxtaposed but there is little framework development. Category C embraces microbial mud-mounds. Category D comprises buildups of biodetrital origin. (Bridges et al., 1995).

The following Carboniferous carbonate producing organisms are known (Bridges et al., 1995), see figures 10 and 11.

- *Calcareous algea* (Cyano bacteria, Solenoporacean, ancestral red algae).
Cyano bacteria are a large and varied group of bacteria which posses chlorophyll and carry out photosyntheses. They do not have chloroplasts. They form stromatolite colonies in fossil rocks and are believed to have been the first oxygen producing organisms. (Oxford dictionar of Earth Sciences, 2003). Solenopora is a class of marine algea, most of them red in colour. Whose basic shape is filamentous or membraneous. They tend to occur at greater depths than the green algae and they are among the oldest groups of eukaryotic algea , known from the Cambrium onwards. In Dinantian times they formed nodular masses made up of close-packed tubes. (Allaby & Allaby, 2003). Nutrients for algae are oxigen, carbon, nitrogen and phosphorus organic and inorganic matter. Calcareous algae are autotrophic lifeforms related to the T and C factory.

- *Phylloid algea*
Phylloid algae is a term referring to paleozoic calcareous algae characterized by leaf-like growth forms. The group includes Udoteacean green algae and ancestral red algae. In cross sections they look like thin sinuous lines. (Flügel, 2010). Phylloid algae are autotrophic lifeforms related to the T and C factory.

- *Bryozoa*
Phylum of small, aquatic, colonial animals, related to the brachiopoda; many colonies possess a well developed, calcite skeleton which comprises microscopic, box like divisions, each housing an individual animal possessing ciliated tentacles which surround the mouth. Bryozoans have occurred abundantly from the Ordovicium until present day. (Allaby & Allaby, 2003). The Bryozoa, also known as Polyzoa, Ectoprocta or commonly as moss animals, are typically about 0.5 millimetres long, they are filter feeders that sieve food particles out of the water. Most marine species live in tropical waters, but a few occur in oceanic trenches, and others are found in polar waters. Bryozoa are heterotrophic animals related to the M, C and T factory.

- *Stromatoporids*
Extinct group, regarded as a phylum with no modern representatives. Stromatoporids are calcareous masses built up of horizontal layers and vertical pillars. The calcareous skeleton is called the coenosteum. They are found in limestones of Cambrian to Cretaceous age. (Allaby & Allaby, 2003). Stromatoporids are heterotrophic animals related to the M, C and T factory.

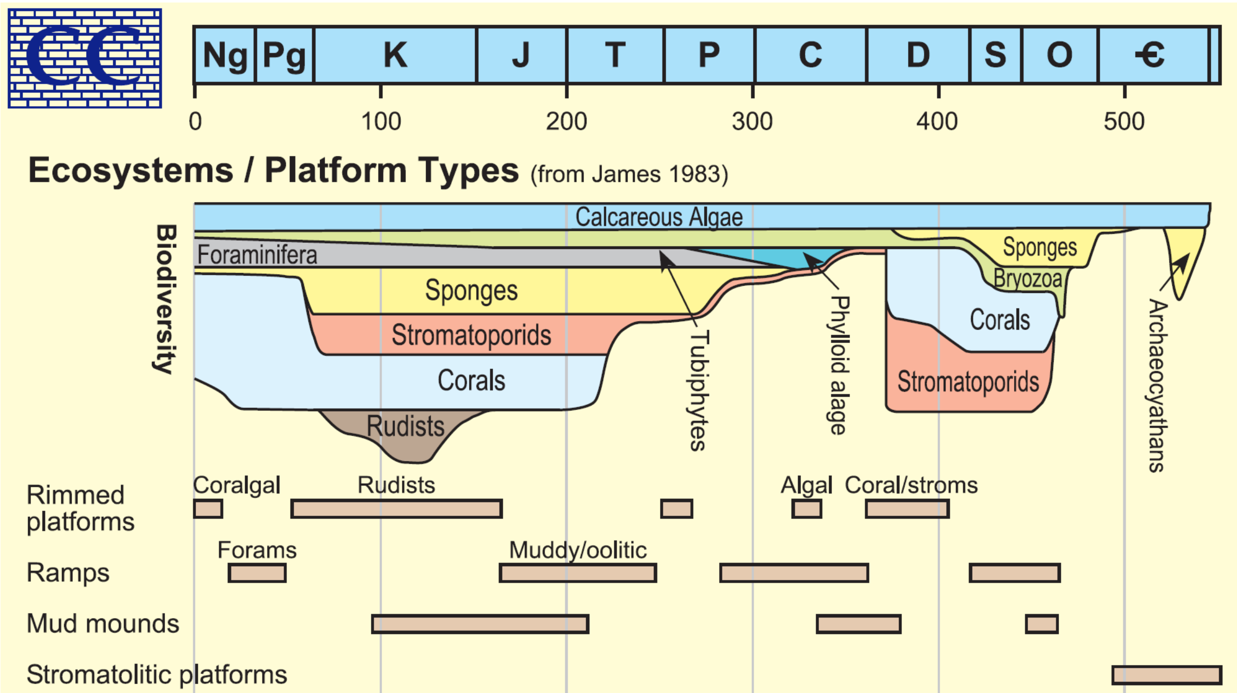


Fig 10: types of carbonate producing organisms, throughout the Phanerozoic.
http://www.cambridgecarbonates.com/

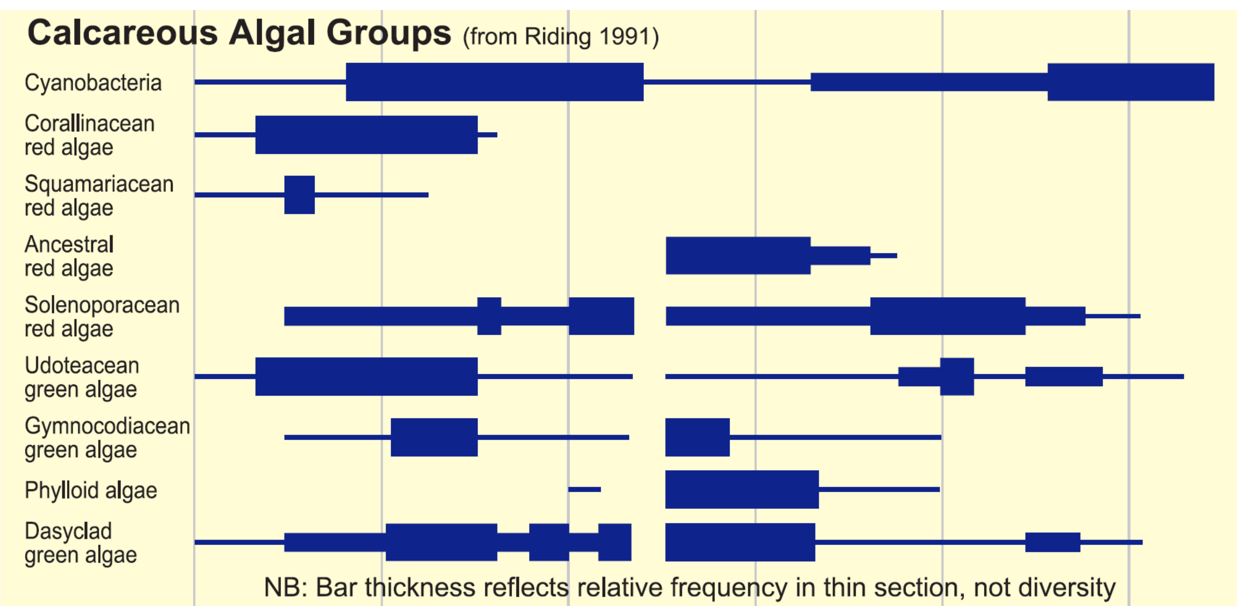


Fig 11: Calcareous algeal groups, throughout the phanerozoic. http://www.cambridgecarbonates.com/

Early Carboniferious build-ups from Belgium, Ireland and the English Midlands have been described as Waulsortian. Lees and Miller (1995) define the term Waulsortian as: build-ups which display a series of generations of mud development (polymuds). They contain at least one of the four depth-related skeletal assemblages defined by Lees at al. (1985) (see figure 9 for the A, B, C and D skeletal types), and they are of Tournaissian or early Visean age.

Bridges et al. (1995) distinguished five distinctive types of Dinantian build-ups:

1. Fenestrate bryozoan-sponge spicule build-ups
2. Crionoid-bryozoan build-ups
3. Crinoid-brachiopod-fenestrate bryozoan build-ups
4. Coralgal-aphralysia and bryozoan-coralgal build-ups
5. Trepostome-microthrombolite build-ups

Types 1, 3 and 5 are mainly in the form of mud-mounds, but many examples of build-up types 2 and 4 cannot be regarded as mud-mounds. Regional tectonics in the form of extensional events caused reactivation of intra-basinal structures resulting in submarine topography which formed nucleation sites for mud-mounds in basinal environments. According to Bridges et al. (1995), types 1 and 2 formed in deep-water settings during the Courceyan to Mid-Chadian. Oceanic upwelling is considered a primary source of the nutrients which supported the microbial activity of type 1 build-ups. The build-up types 3, 4 and 5 formed in mid- to shallow-water shelf, shelf margin and intrashelf basin settings during the Holkarian-Brigantian stages.

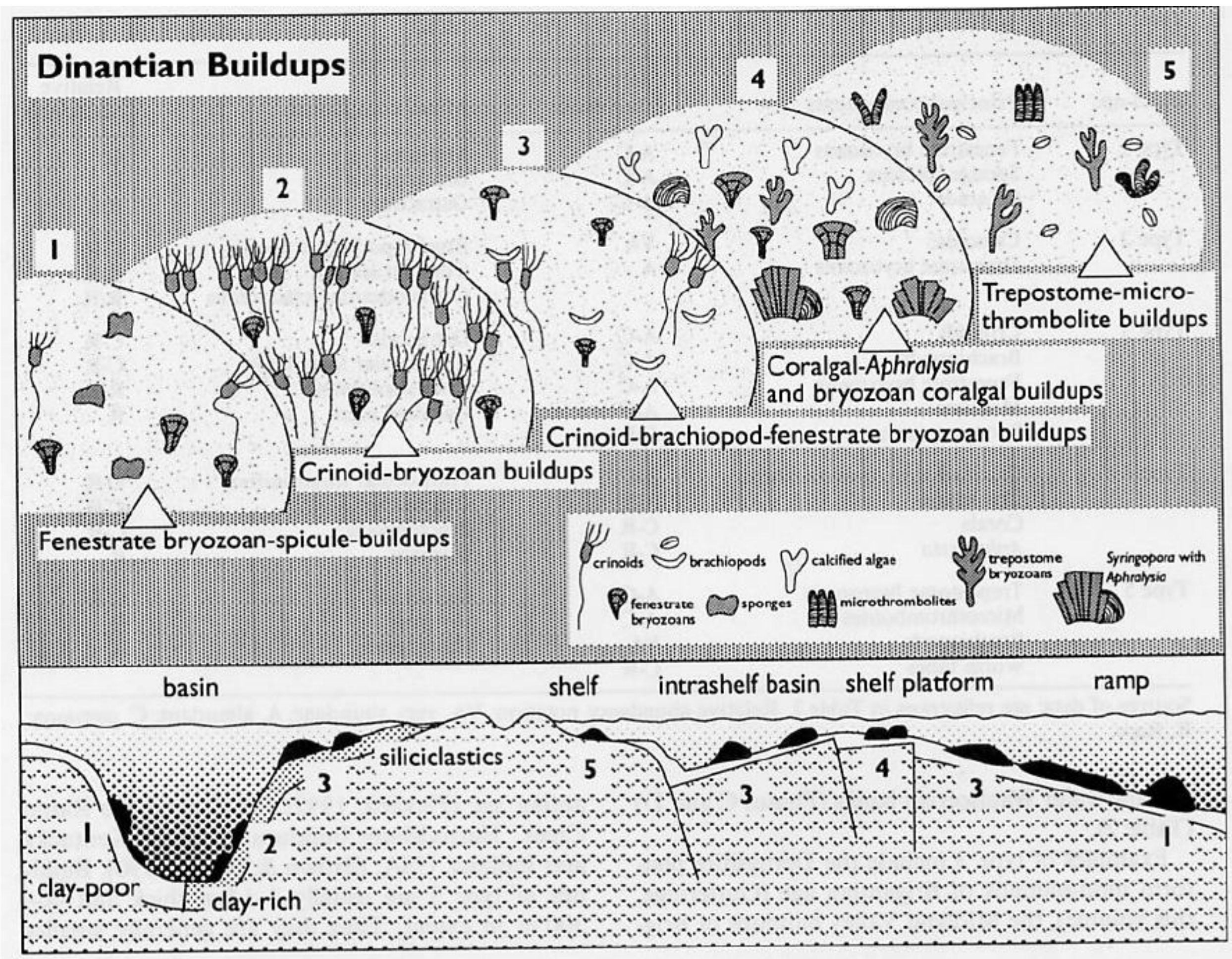


Fig. 12: The 5 types of early Carboniferous build-up and their characteristic environmental settings. The build-up types are distinguished by the principal skeletal components. (Bridges et al., 1995)

Late Dinantian mud mounds were deposited on carbonate shelves and shelf margins whose depths were within the range of fourth and fifth order sea-level variantions. The growth of carbonate mud mounds in carbonate shelf settings was often terminated by subaerial exposure. Also the Asbian Brigantian boundary is supposed to be subsidence following an extensional event. According to Bridges et al. Asbian Brigantian mud-mounds extinction made place for flat topped platforms. In conclusion; Dinantian carbonate geometries vary from mud mound geometrie to flat topped platforms and ramps.

Boreen and James (1993) have reported bryozoan-sponge mounds nowadays forming at depths greater than 100m off the shelf of South-Eastern Australia. These mounds are forming in the vicinity of a zone of active upwelling and are showing growth rates of approximately 1,05 m/kyr. This supports to some extent the contention of Wright (1991) that regional upwelling may have been a significant source of nutrients which enabled the large deep-water microbial build-ups (type 1) to grow, (Bridges et al. 1995). A second possible source of nutrients is that of cool-water hydrothermal seeps. Such hydrothermal seeps have been postulated to explain type 5 build-ups in Newfoundland. However the observation that most type 1 build-ups, dominated by microbial muds, formed in deep ramp, mid-ramp and shelf slope compares well with an oceanic supply of nutrients from passing upwelling currents.

All structures show signs of early lithification and resistance to adverse flow conditions (Bridges and Chapman, 1988). In conclusion, Dinantian carbonate geometries; mud mounds, flat topped platforms and ramps can be found at deep shelves, mid shelf slopes, extensional basins and deep water environments at depths ranging from 0-100m.

Algae

Since algae are a main component in the carbonate precipitatian during the Dinantian, expecially type 1 mud mounds, extra information on the formation of microbial mats is required. Microbial mats are a minute life form; a micro-organism, especially a bacterium in a highly organized multi-layered sheet of micro-organisms. As described by Dupraz et al. (2009); their growth as a carbonate precipitant is controlled by: the alkalinity of the water and organic matrix in which the mineral will nucleate. The alkalinity is influenced by extrinsic and intrinsic factors. The extrinsic factors controlling carbonate precipitation are: CO2 (degassing), water input and evaporation. The intrinsic factors controlling carbonate precipitation are: respiration and photosynthesis (see figure 13).

Alkalinity, extrinsic factors

The dissolved CO2 content strongly influences pH conditions of the water and therefore controls whether CaCO3 (Calcium Carbonate) will dissolve or precipitate. Water input from an alkaline source, for example a fluvial influx, influences the carbonate precipitation rate. Evaporation changes the water saturation content for dissolved calcium, the bigger the saturation rate the more probable that CaCO3 will precipitate instead of dissolve.

Alkalinity, intrinsic factors

Respiration (see figure 14) and photosynthesis are strongly dependent on light and nutrients (Dupraz et al., 2009), which is critical in determining the flow of carbon through the mat ecosystem, and with that, the individual types of metabolism. Nutrients increase with greater depth, whereas light reduces with increasing depth. Optimal depths for microbial mats to grow are between 0-100m. Oxygen is not a key factor needed for respiration (see figure 14) and can be replaced with other oxidation reactions induced by NO3, MnO2, FeOOH, SO4 and HCO3, forming in an anoxic environment.

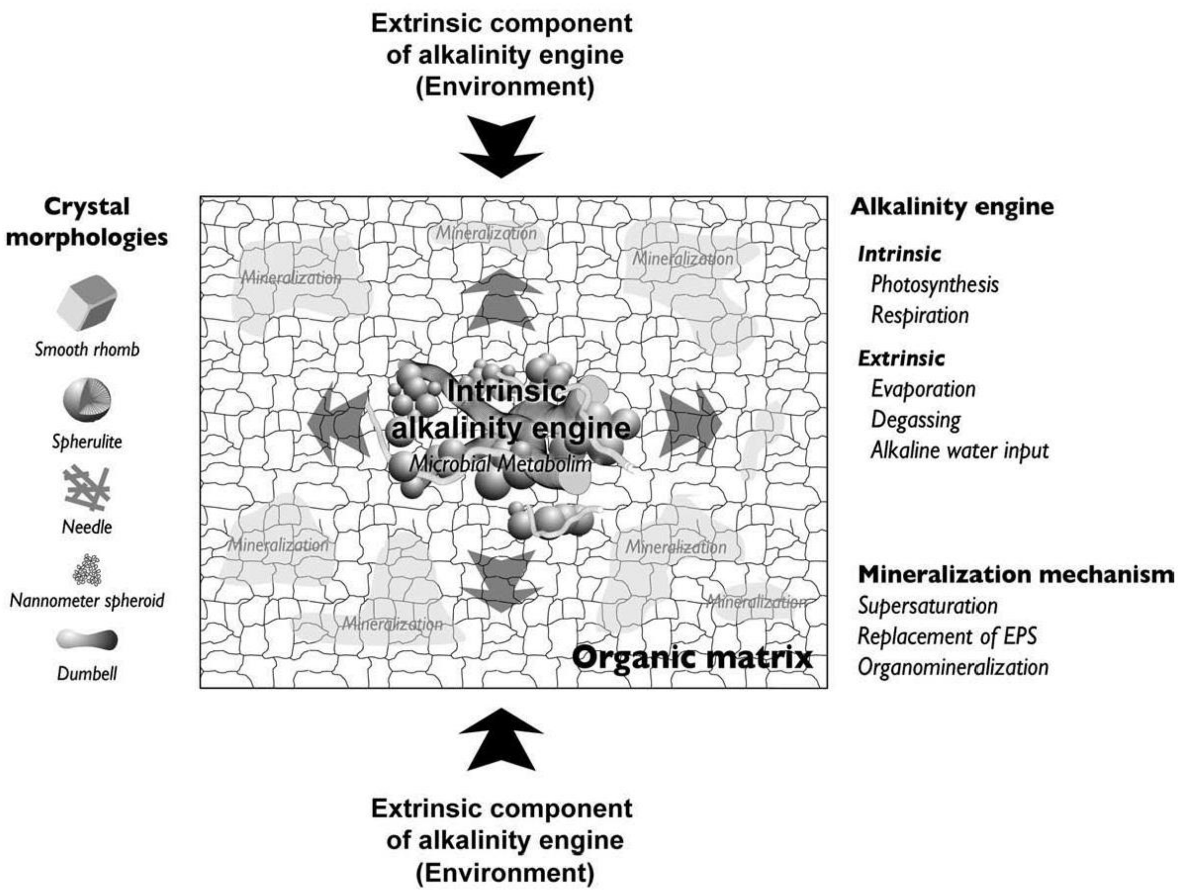


Fig. 13:Factors contributing to the organic mineralization. It can be divided into two closely coupled elements: the alkalinity (engine) and the organic matrix in which the mineral will nucleate. The alkalinity engine has two components: an intrinsic (microbial metabolism) and extrinsic (the environment) component. The EPS matrix, which is also the result of microbial activity, is not part of the alkalinity engine. This matrix can strongly influence mineral shape and composition, producing an array of crystal morphologies and mineralogies. (Dupraz et al., 2009)

In conclusion: in order to grow microbial mats nutrients are needed such as O, C, N and P. These nutrients are more abundant at greater depths, and needs upwelling in order to reach the water column with enough light for photosynthetic processes. A typical depth related to these processes is: 0-100m. An alkaline environment induces carbonate precipitation from microbial mats by, either warm temperatures, fluvial water influx or by dissolution of CO2. The best place for Dinantian microbial mat build-ups would typically be near a continental shelf at warm to moderate temperatures (latitudes) near an upwelling zone.

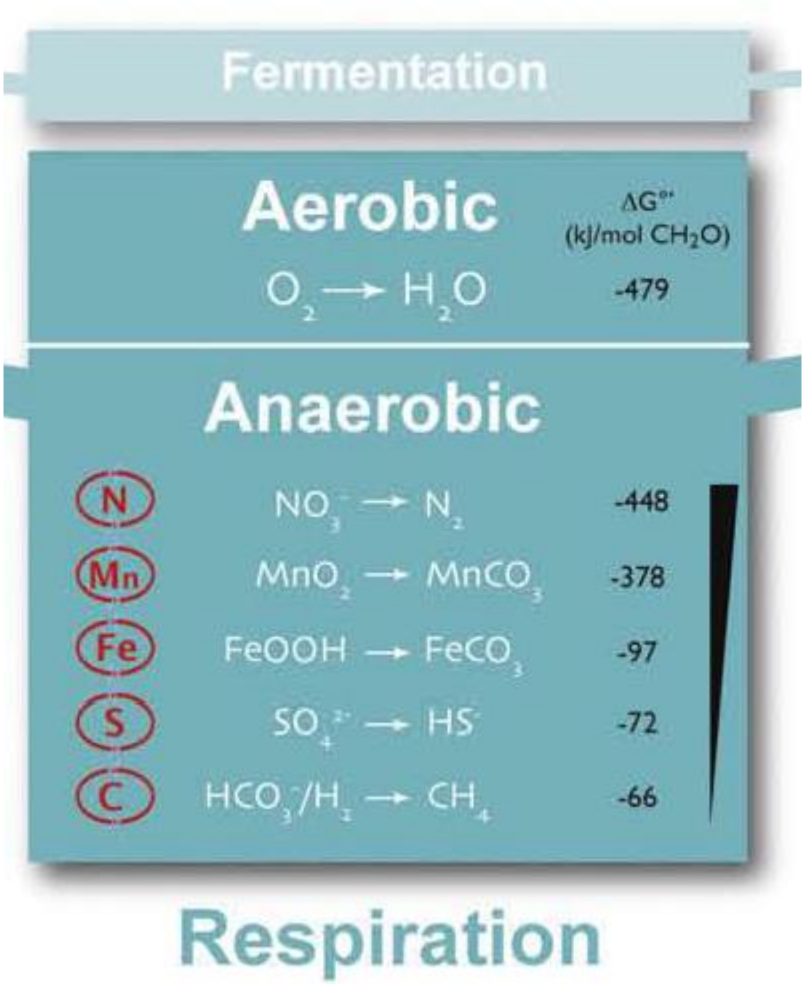


Fig. 14: Respiration formula's for microbial mats. (Dupraz et al., 2009).

Results

In order to review the prospectivity of the Northern onshore Dinantian carbonates, all well results need to be compared to literature and mapped carbonate build-ups need to be assessed as potential reservoirs and traps. Furthermore, comparison with analogues and the regional tectonic setting is discussed. This will tell us more about: reservoir quality, porosity & permeability, source rock maturation and migration, deposits that might act as a seal. The results will be presented in the following chapters:

- Well information, evaluation and reservoir development
- Geometry of the Dinantian carbonate build-ups in the Dutch Northern onshore
- The geological history of the Dinantian in the study area (Northern onshore Netherlands)
- Analogues for Dinantian carbonate build-ups, Northern onshore Netherlands

A summary of all these results is given in the chapter: “Discussion: prospectivity review”.

Well information, evaluation and reservoir development

Introduction
Two wells reached Dinantian aged carbonate build-ups in the Northern onshore Netherlands: LTG-01 and UHM-02 (see figure 1 for the location of these wells). The wells drilled in the South of the Netherlands penetrating the Dinantian section have been used for comparison. Due to the Variscan orogeny they cannot be compared to the diagenesis and burial history of the Northern onshore. As described before, the carbonate production geometry was different from the South due to the influence of the London Brabant Massif. Therefore , these two wells provide the only information present on diagenesis, burial history, porosity, permeability and reservoir quality for the Northern onshore Netherlands. in order to provide a solid conclusion and a theoretical model for reservoir potential, the wells are compared to known Dinantian reservoir types and karstification processes are discussed.

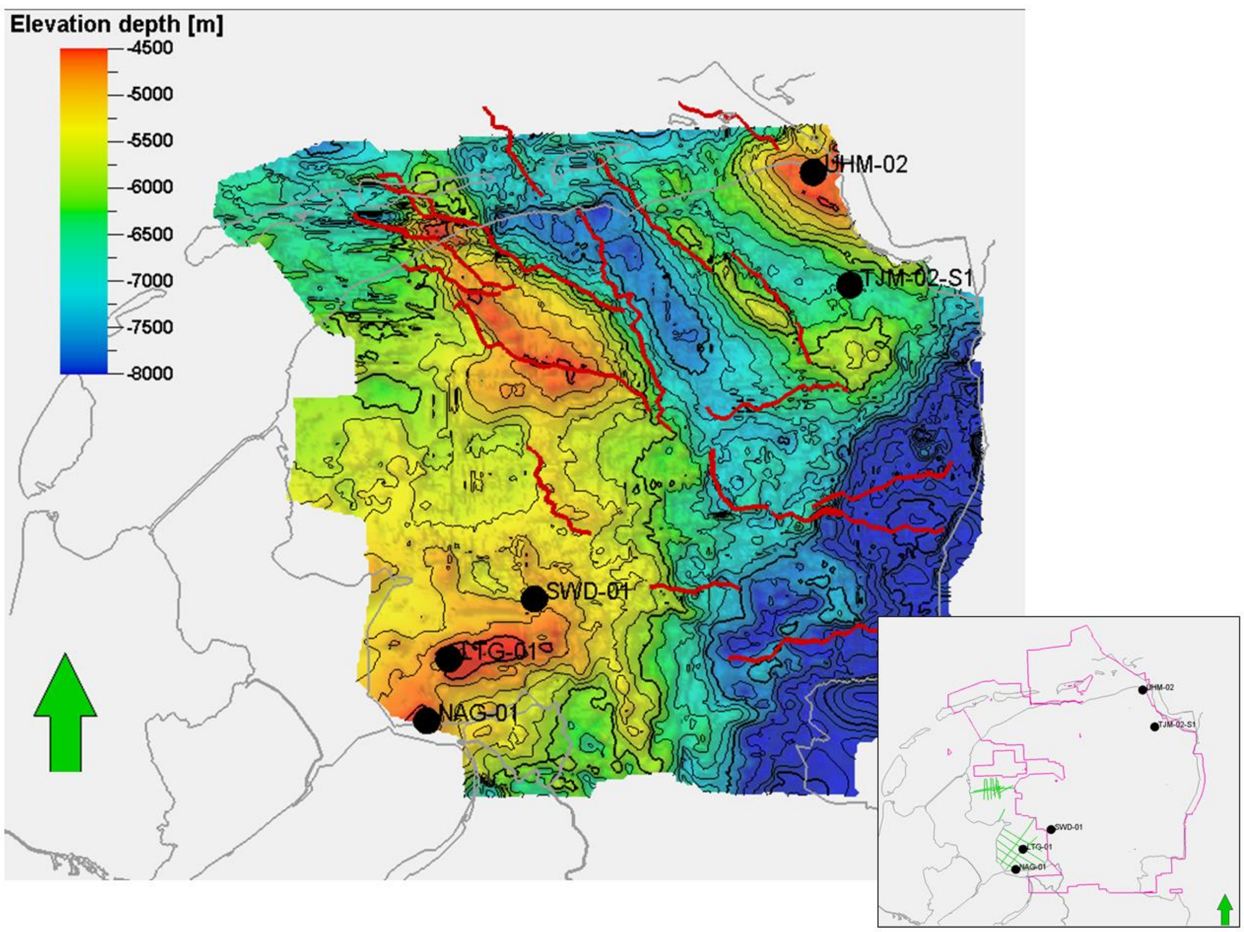


Fig. 1: Top Dinantian depth surface, with wells penetrating the pre-Westphalian. Red lines indicate faults.

Well correlation

Although well control in the study area is limited. Well correlation has been carried out. Two well correlation panels have been made: a South section and a North section (see figure 2) in order to compare Dinantian log response in both carbonate successions. The used log information comprise: gamma-ray (0-450 gAPI), neutron (0,45- -0,15 m^3/m^3) density (1-2 gr/cm^3), sonic (40-140 µs/ft) and resistivity (0- 10^8 Ωm). The result of these well correlation panels can be found in appendix **I**.

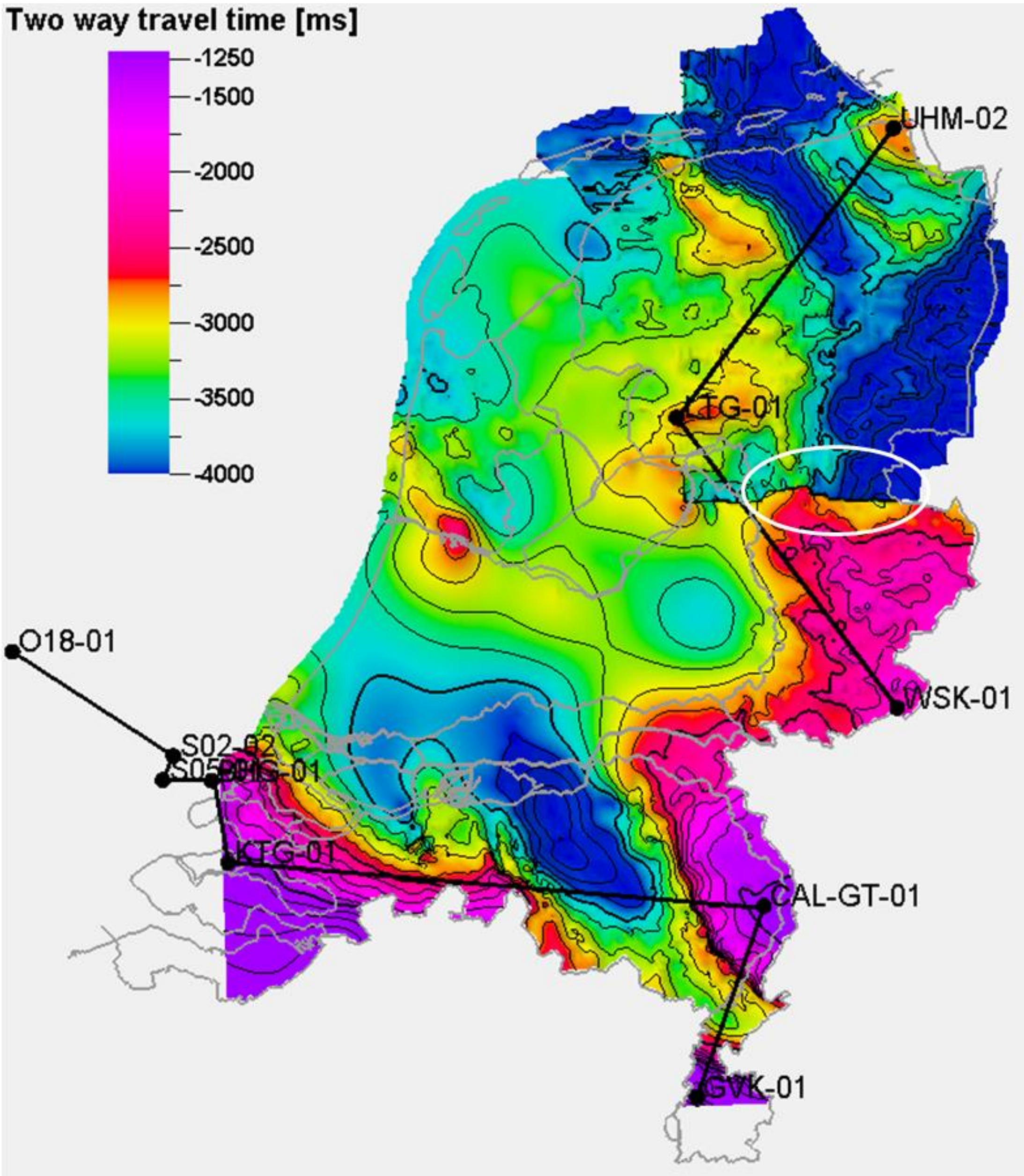


Fig. 2: Outline of the Netherlands, with placing of the wells and placing of the well correlation sections: North and South. The surface represents Top Dinantian in TWT (ms), The Northern onshore part has been mapped in this study, the Southern onshore part is being mapped by TNO (Ed Duin) and represents work in progress. The Northern onshore part comprises of more seismic data compared to the Southern onshore part, therefore the Northern onshore part has been mapped in more detail. The white circle represents an area of limited seismic data, where the uncertainty in interpretation increases.

Well section South.
The Dinantian succession has a specific log response. Overall in the South section, the sonic drops to around 45-50 µs/ft, this is even the case when chalk overlays the Dinantian Carbonates. 45-50 µs/ft is a typical value for limestones/anhydrate. The resistivity log increases to around 900 Ωm (+/- 500). An increase suggests less salt in the water, the presence of hydrocarbons (not here) or less water (less porous). When a neutron log is present , it decreases to 0 m^3/m^3. When a density log is present it becomes a straight line around 2,7 g/cm^3; consistent with limestone specific density (2,3-2, 7 g/cm^3). The straight line may represent a tight formation. Note: all wells in this correlation panel are drilled on highs (instead of flanks). The overall patterns seems to give the idea that the package consists of tight limestone with almost no porosity and with little intra Dinantian changes. Cores taken from these wells show karstification features with infill from overlying formations.

Well section North
The Dinantian succession has a specific log response. Overall in the North section, the sonic drops to around 50 µs/ft, regardless the overlying formation. The sonic log in the Dinantian succession is mostly a straight line, with the exception of a few spikes. The resistivity log is not present in UHM-02 and LTG-01 of the Northern section and cannot be compared. The neutron log is decreases to 0 m^3/m^3. The density log becomes a straight line around 2,65 g/cm^3; consistent with limestone specific density (2,3-2,7 g/cm^3). The straight line may represent a tight formation. Note: all wells in this correlation panel are drilled on highs (instead of flanks). The overall patterns seems to give the idea that the package consists of tight limestone with almost no porosity and with little intra Dinantian changes. WSK-01 is significantly different from UHM-02 and LTG-01, however this well is outside the study area and is represented in different tectonic regime (see figure 2). In the WSK-01 and the UHM-02 well, the Dinantian succession is overlain by the Geverik member.

Tournaisian section is absent in the Dinantian carbonate build-ups encountered in the Northern wells UHM-02, LTG-01 and WSK-01, contrary to the South where both Visean and Tournaisian are present in all wells. This could be related to climate change in these periods, affecting the carbonate build-up. It could also be related to the paleotopography that differed very much in the South due to the presence of the London-Brabant Massif and the Variscan front. The Southern section shows massive uplift and erosion at some places. The wells in the Southern section mostly comprise the Beveland member, the Schouwen member and the Goeree member, whereas the Northern ones only have a thin Beveland (UHM-02) or no Beveland present (LTG-01 and WSK-01).

UHM-02
The Visean is complete, the Tournaisian on the other hand is missing. The Beveland member starts at the dolomitized limestone layer (5130 mTVD). The Zeeland formation has a density of 2,70 gr/cm^3 and this is very consistent throughout the whole succession. The Beveland member has a density of 2,72 gr/cm^3. In this member 2 big events are evident from the logs; a rapid increase of both the sonic and the neutron log, together with a decrease in the density log. The density drops to 2,50 gr/cm^3. The gamma-ray log does not show a lithology change, therefore these features probably represent fractures/faults or an erosive boundary.

LTG-01
The Visean is incomplete; Asbian and Brigantian are not present, the Tournaisian is also missing. Dolomitization is encountered at 5020 m TVD, but it is not classified as Beveland member. A big event is evident from the logs at 4700m TVD. The neutron log increases and the density log decreases, while the sonic log and the gamma-ray log don’t change. The neutron/density logs show signs of porosity, because

the sonic log does not react, this suggests vuggy porosity. The mudlog states; no visible porosity , but infill of fractures with dolostone and calcite or an erosive boundary.

Van Hulten (2012) compared UHM-02 and LTG-01 in a well correlation and found the following: a number of third order cycles can be distinguished, characterized by periodically arrested reef growth (see figure 3). Karstification linked to sea-level low stands has been noted at a few intervals in LTG-01 (Van Hulten & Poty, 2009).

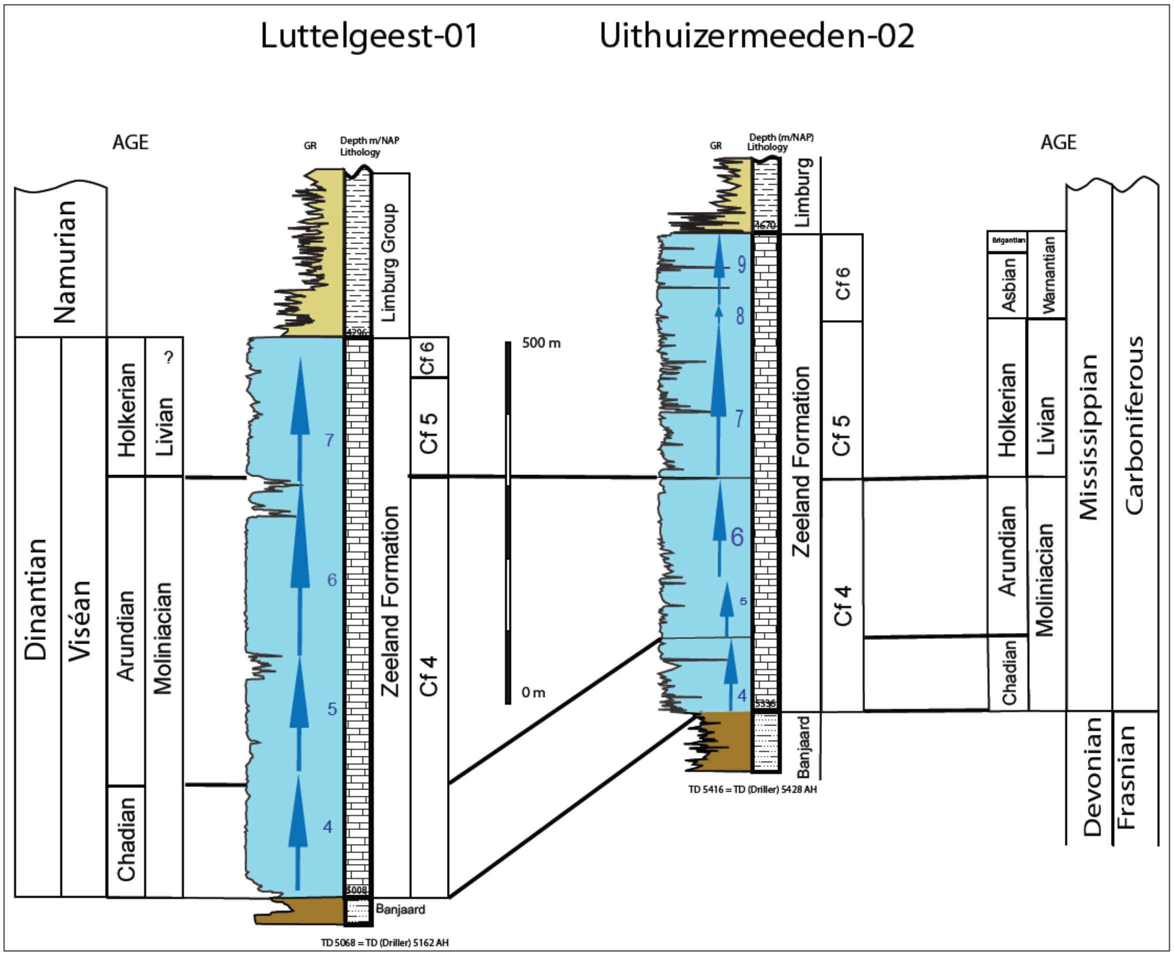


Fig. 3: Cross section showing a stratigraphic comparison between the LTG-01 and UHM-02 wells. The Gamma Ray (GR) log of both wells is shown for comparison. Both wells reached TD (Total Depth) in the top of the Famennian clastics. The arrows shows widely recognized 3rd order sequences (Poty et al., 2002). The age interpretation is based on foraminifera (Cf zones). Contrary to the UHM-02 well , the reef growth in LTG-01 was terminated before the end of the Visean. From Van Hulten (2012)

Figure 4 shows a well correlation panel of UHM-02 and LTG-01 carried out in this study. More information on core data can be found in the next subchapter.

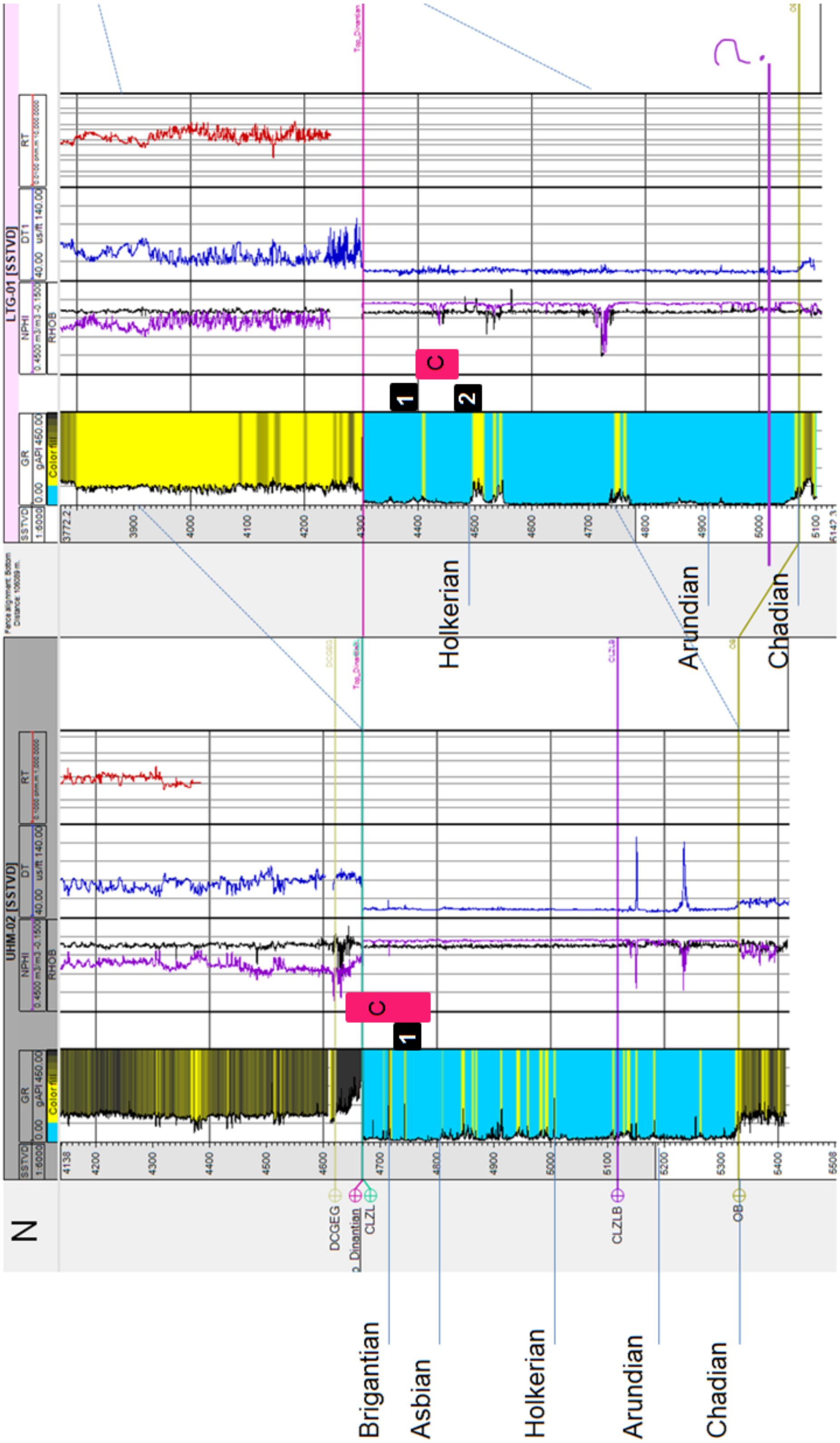


*Fig. 4: The log information as presented in the appendix **I** "well correlation", with placing of the cores taken. The black bars with numbers indicate the placing, not the actual thickness of the core taken. Pink square (with C) indicates the placing of the thin sections.*

Core descriptions
This subchapter contains all relevant information on reservoir quality from the wells UHM-02 and LTG-01, by use of core descriptions, thin section descriptions, interpretation of the stratigraphy, and porosity and permeability measurements. Operators provided well testing information and literature is compared to the findings.

Geluk et al. (2007. And references therein) states that Dinantian carbonate successions comprises of the following: The Zeeland Formation is subdivided into three members, from bottom to top these are the Beveland, Schouwen and Goeree Members:

- The *Beveland Member* (Tournaisian to early Visean, V1) is a sequence of medium- to dark-grey, coarse-crystalline dolomites with black residual organic matter (up to 5.5 wt%, commonly concentrated in thin laminae or around recrystallized dolomite) and locally well-developed intergranular to vuggy porosity. In places, limestone, claystone and siltstone intercalations occur.
- The *Schouwen Member* (middle to late Visean, V1-V3a) is composed of grey to brownish limestones. These limestones are mostly micritic, locally oolitic and abundantly fossiliferous, indicating depositional environments ranging from lagoonal or intertidal to shallow subtidal. Intergranular, bituminous material is often present. Thick breccia units, possibly of both dissolution and dynamic origin, occur locally within and on top of the member.
- The *Goeree Member* (late Visean, V3) is a succession of grey to black limestones, which are thin- to thick-bedded, and often partly silicified. Black shales and cherts, and also thin tuffaceous beds occur in the upper part of the member. On structural highs, this member may be represented by microbial or cryptalgal reef mounds. Faults had a major effect on the facies

Note: These descriptions about Dinantian successions are based on wells and outcrops in the South of the Netherlands, nevertheless this background information is used in order to describe the Northern onshore carbonate succession.

Cores are described by the Dunham (1962) classification system, as presented in figure 5 and porosity is described by Choquette and Pray (1970) porosity classification system, as presented in figure 6.

The carbonate cement classification used, is as follows:

Micrite	1-4 µm	grainsize
Microspar	5-30 µm	grainsize
Spar	30-50 µm	grainsize

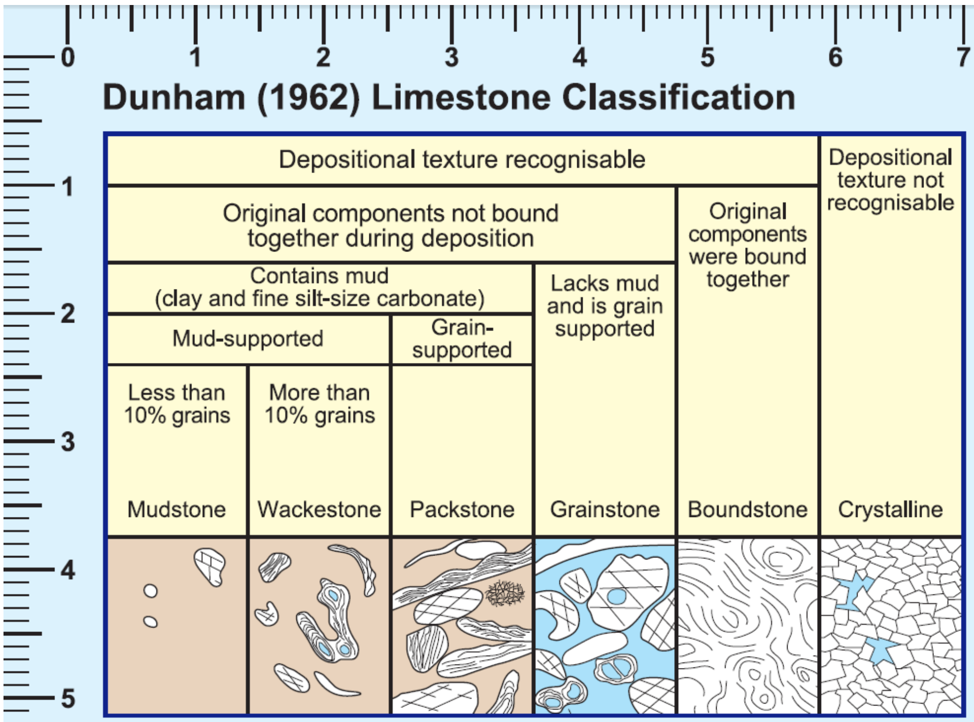


Fig. 5: Dunham limestone classification system. (http://www.cambridgecarbonates.com/)

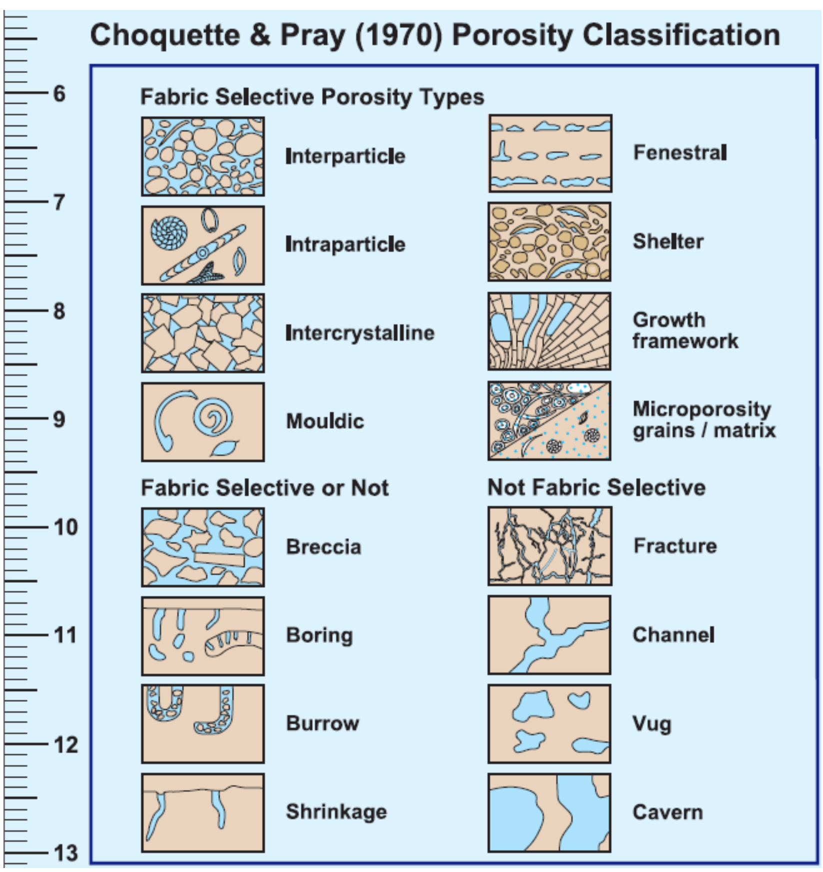


Fig. 6: Porosity classification system. (http://www.cambridgecarbonates.com/)

LTG-01
Drilled by Total in 2004.
No drill stem tests: dry hole and no flow.
Temperature: 200°C
Dinantian Carbonates: 4303 m (TVD NAP) – 5070 m (TVD NAP) = 768 m of carbonate build-up.

Core interpretation and thin section interpretation were done by Daniel Vachard, Total (2004) and Van Hulten & Poty (2009). The cores were taken at 4376 m – 4378 m TVD = covering 2 m, and at 4470 m – 4473 m TVD = covering 3 m. Thin sections were taken at 4380 m – 4470 m TVD = covering 90 m. See figure 1 for the location in the well. The carbonates are covered by shaly clastics interpreted as Namurian A age and the well TD'd in clastics of Upper Devonian interpreted as Famennian of age.

Core description:
The dominant lithology is a grey limestone (see figure 5) . Analysis of the core taken about 20 m below the top of the carbonate section revealed a composition of 99% limestone. Dolomite is rare but present in the carbonate section of the well. At the base of the carbonates succession, more dolomite streaks were described. Grainstones have been found, however crinoidal packstone is more common for the mount facies. On logs (see figure 2) two or three spikes are visible at 4770m that are associated with vuggy porosity, this may indicate a stratigraphic subdivision. Gamma peaks may also be associated with mineral veins, quite common in Dinantian carbonates.

Thin Sections:

Depth m (TVD)	Interpretation (Vachard, 2004)
4470,00 m	Neosparitized wackestone/packstone. Black shales. Finely granular sandstone.
4464,00 m	Fossiliferous microfacies. Tectonized recrystallized limestones (with Tournasian infill). Siltstones. Foraminifers and algea microfacies of Visean age.
4458,00 m	Microstylolitized, compacted, oolitic packstone. And tectonized limestones.
4452, 00 m	Oolitic and bioclastic grainstone with radiole. Bioclastic packstone with crinoids. Tectonized limestone. Silicite (with tournasian infill). Black shales. Siltstone
4446,00 m	Tectonized limestone. Siltstone. Rare wackestones without microfossils. Black shale
4440,00 m	Tectonized limestone. Siltstone. Rare fossiliferous microfacies. Silicite (with Tournasian infill).
4434,00 m	Bioclastic wackestone. Black shales. Tectonized limestone. Rare finely granular sandstone.
4428,00 m	Bioclastic wackestone. Tectonized limestone. Black shale. Siltstone.
4422,00 m	Tectonized limestone.
4416,00 m	Tectonized limestone.
4410,00 m	Tectonized limestone. Silicite.
4404,00 m	Tectonized limestone. Visean microfacies of bioclastic wackestone. Silicite.
4398,00 m	Tectonized limestone. Black shale.
4392,00 m	Tectonized limestone (rare crinoids). Black shale. Siltstone.
4376,00 m	Bioclastic grainstone. Tectonized limestone.
4386,00 m	Tectonized limestone. Black shale. Siltstone.
4380,00 m	Tectonized limsestone. Black shale. Siltstone.

Table 1: Thin sections described by Daniel Vachard; Total, 2004.

Reservoir quality:
The reservoir quality in the well is poor, with matrix porosity below 2%. This resulted in very low permeability; 0-9 mD. Only a few fracture zones were encountered on FMI. Two fracture zones correspond with the gamma ray peaks and indicate karstification horizons. The FMI indicated also a structural overprint with fractures in a N130-140 direction. Well testing recovered poor pressure data. Tests did not recover any hydrocarbons. There were only slight gas shows from the mud log. Mud logging hardly recovered more methane than can be expected from background noise. Fluid inclusion studies on core material were not conclusive but suggested that there may never have been methane trapped in the structure. (Van Hulten & Poty, 2009. And references therein).

Conclusion:
Upper part of the Visean is missing; Luttelgeest contains only lower Visean. Several tectonized limestones and silicite show infill of Tournaisian aged fragments, this suggest karstification processes. The tectonized limestones could also be related to reworked Tournaisian (Vachard, 2004). This interpretation is debatable for, there is no Tournaisian present in LTG-01 and if it would have been present infill from a layer below is uncommon. A major play element is the reservoir quality of the Dinantian age carbonates. The presence of dolomitization and karstification are assumed to be important for reservoir quality. The well LTG-01 shows some permeability streaks but the overall porosity is very low. There are dolomitic intervals but they do not show improved reservoir quality. Interbedded shale units may form a baffle to vertical fluid flow. Below the carbonate section Famennian clastics were encountered. The Dinantian carbonates are overlain by shaly deposits, which is determined on 50 m of washout, also no dating has been carried out on these cuttings. Whether Luttelgeest drowned or eroded remains unclear and further research is needed.

UHM-02
Drilled by NAM in 2002.
Well productivity (water): 103M^3/D at 50 BAR drawdown, 5154m (Beveland member)
Gas show contains 85 % Nitrogen at a temperature of 200°C
Dinantian Carbonates: 4682 m (TVD) – 5344 m (TVD) = 662 m of carbonate build-up.

Core interpretation and thin section interpretation were done by Gutteridge (2002). The core was taken at 4751 m – 4758 m TVD = covering 7 m, thin sections were taken at 4676m – 4761m TVD = covering 85 m. See figure 1 for the location in the well.

Core description:
The core comprises of 6.74m of limestone overlain by 0.2m of shale (interpreted as Geverik member). The limestone consists mainly of sorted grainstone/packstone with some wackestone/packstone beds. No sedimentary structures are present; bedding is poorly defined and marked by subtle changes in color, sorting and mottling, occasionally emphasized by the presence of stylolites (figure 6). The majority of bioclasts are fragmented and rounded and include foraminifera, algae, calcispheres, echinoderms, bivalves and brachiopods. Occasional large allochems of solitary rugose corals and

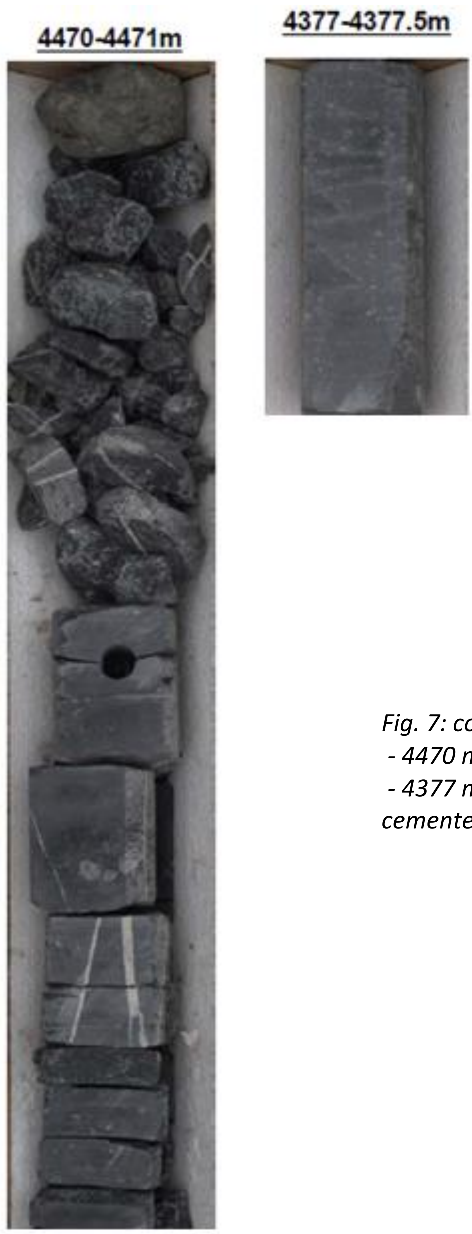


Fig. 7: core taken from LTG-01:
- 4470 m: cemented fractures.
- 4377 m: grey limestone, with cemented fractures

brachiopod valves can be seen in the core. Bioclasts have been micritised and peloids are locally common. Some fragments also have a partial coating of micrite. Intervals of bioclast wackestone/packstone with bioturbation mottling are also present. The shale at the top of the core contains silty laminations and compacted isolated ripples. The shale is in sharp contact with the underlying limestone. See figure 7 for a detailed description done by Gutteridge (2002).

Fig. 8: Stylolites present within bioclast peloid wackestone/packstone. Cut by a another stylolite that has been partly opened and has pores at the apexes. Early spar-filled cavities are also present. These may have formed during an early phase of exposure and karstification. Core depth 4753.34m. (Gutteridge, 2002). Right picture taken by Bastiaan Jaarsma (EBN, 2013), coin for scale.

Thin sections:
Thin sections of selected cutting samples were examined, leading to the following microfacies description:
- Wackestone/packstone: This is the dominant microfacies type; it was deposited in a low to moderate energy subtidal environment just below to just above wave base.
- Peloid grainstone: This was deposited in a moderate to high-energy subtidal environment above wave base but in conditions of relatively slow sedimentation. This microfacies may have been part of a carbonate sand body associated with a carbonate shelf.
- Calcite crystals: indicate the presence of fractures or vugs in the carbonate interval.

Sedimentological interpretation:
The majority of the cored section was deposited in a moderate to high-energy reworked subtidal environment just above normal wave base. The diverse bioclast assemblage indicates deposition in open marine conditions and the presence of micritisation and coating of allochems indicates episodes of relatively slow sedimentation. The overall depositional setting was part of a carbonate shoal complex associated with a the inner part of a carbonate platform. The intervals of bioturbated wackestone were deposited in a moderate to low energy subtidal environment just below normal wave base or in a sheltered subtidal setting within the carbonate sand body. Cutting samples suggest that the succession comprises cyclic subtidal carbonates deposited on a carbonate shelf or ramp. Carbonate cycles are dominated by low to moderate energy subtidal carbonates that shallow-up into higher energy subtidal and occasional peritidal conditions. Since the core shows no evidence of cyclicity, the scale of cyclicity is thought to be larger than the core (i.e. on the order of at least 10m). (Gutteridge, 2002)

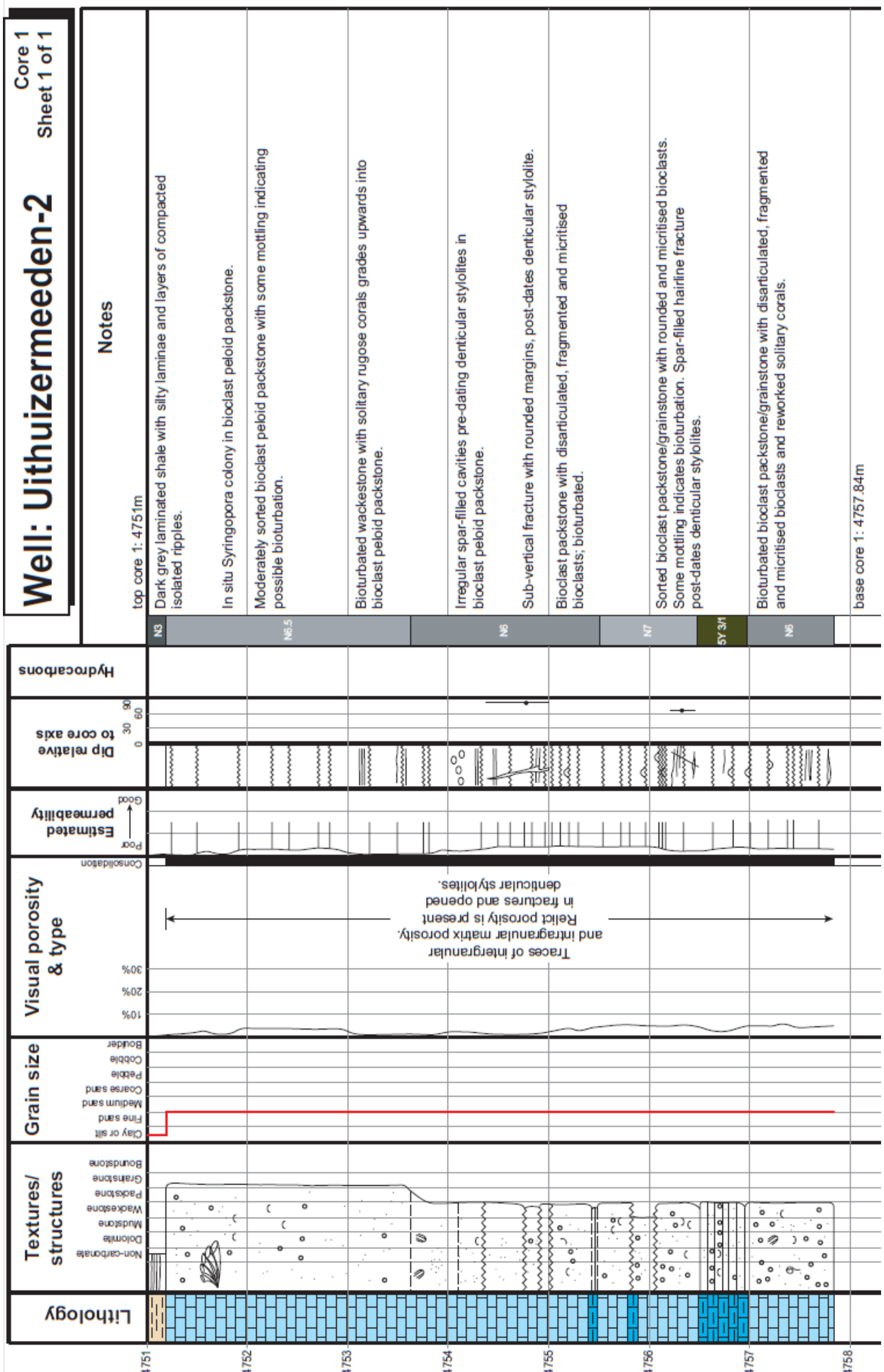


Fig. 9: core description and interpretation (Gutteridge, 2002).

Porosity:
Traces of intergranular and intragranular matrix porosity are present throughout the core and appear to be concentrated in higher energy grainstone facies. Intergranular and intragranular porosity has been reduced by compaction and precipitation of calcite cement. Aragonite bioclasts such as bivalves have been dissolved but the biomoulds have been infilled by calcite. The core contains multiple stylolites that have amplitudes of 2-9cm with clay concentrations along the stylolite (figure 6). They occur as single denticular stylolites and as anastomosing stylolites. The stylolites appear to have been opened with the development of porosity at the apexes of the stylolites. This is a reflection of stress relaxation and implies an episode of uplift after pressure dissolution during burial. The core contains cm-sized fracture-like pores, vugs and biomoulds that are present at various levels in the core (figure7). They are cut by, and therefore pre-date the formation of the stylolites. These pores are irregular in shape with sharp, rounded poorly fitting margins. Some have been partly infilled by bioclastic and peloidal geopetal sediment identical to the surrounding limestone. These pores are infilled by coarsely crystalline calcite cement with some relict porosity. These are interpreted as vugs and biomoulds formed by dissolution as well as fractures enlarged by dissolution. There are also sub-vertical (70°-90° inclination) fractures 0.60 to 0.25m long and are to 2.5mm wide. They cross cut and therefore post-date the stylolites (figure 8). (Gutteridge, 2002)

Fig. 10: Late sub-vertical fracture with rounded margins cuts through two stylolites. Fracture may have originated during burial or uplift and then exploited by karstic dissolution during uplift. The fracture contains relict porosity after precipitation of calcite cement. Core depth 4754.80m. (Gutteridge, 2002)

Reservoir quality:
The matrix porosity is generally very poor with a very poor storage capacity. Matrix porosity appears to be facies controlled and so is likely to be layered following sedimentary cyclicity. Interbedded shale units may form a baffle to vertical fluid flow. The matrix porosity has been reduced by compaction, cementation and pressure dissolution. The fracture-like cavities and vugs may represent early fractures or biomoulds that have been enlarged by dissolution. They may represent an early phase of karstic exposure, predating the formation of stylolites. This may be related to emergence events associated with the depositional cyclicity of the succession. These were later infilled by calcite cement, although some relict porosity is present. This could be related to intra-platform karst as seen in Kashagan (Ronchi

et al., 2009). The stylolites were followed by an episode of uplift with the opening of the stylolites apexes as a result of stress relaxation. Overall porosity remains lower than 4%. (Gutteridge, 2002)

Conclusion:
The core comprises bioclast peloid packstone/grainstone with minor bioturbated wackestone/packstone deposited in a high-energy subtidal setting, probably associated with a carbonate shoal. The carbonate system was drowned with the deposition of a deep marine shale.

- Matrix porosity is very poor with traces of intergranular and intragranular porosity concentrated in the higher energy bioclast peloid packstone/grainstone facies.
- Macroporosity comprises opened stylolites and relict porosity in spar-filled fractures and vugs.
- The cored interval is interpreted as a karstic reservoir with an early set of karst cavities partly infilled by bioclastic and peloidal sediment. These formed during higher order low stands during deposition of the host limestones. A later set of fractures enlarged by karst dissolution formed during uplift; the stylolites were opened at this time.

Karstification
Karstification is the process of carbonate dissolution:
Qs= ionic quotient = $[CO_3^{2-}]$ * $[CA^{2+}]$
Ks= solubility quotient maximum, where:
Qs<Ks represents under saturation and $CaCO_3$ will be dissolved.
Qs>Ks represents super saturation and $CaCO_3$ will precipitate.
Qs=Ks represents an equilibrium (this does not mean that dissolving processes and precipitation processes do not take place). (McLlreath and Morrow, 1990)
The most important factors controlling Ks are: Temperature of the water, pH of the water (mainly influenced by CO_2 content), salinity of the water and water pressure of the above lying water column. Qs is mainly controlled by organic input of the water system. Dissolution or karstification can take place when salinity changes, for example when a marine system is influenced by meteoric input. This happens when relative sea-level lowers and the carbonate system is exposed to meteoric water. This is referred to as meteoric karstification. Also a coastal environment with fresh water input from the hinterland can cause salinity changes due to the mixing of fresh water with saline water. This is referred to as mixing zone karstification. An increase in temperature and fluid input due to hydrothermal circulation during a stress regime can also influence Ks in such a way that dissolution takes place. This is referred to as hydrothermal karstification. Both core descriptions mention dissolution and/or karstification features (on a thin section scale). In the South of the Netherlands, the Dinantian carbonates are known to have been subdued to major karstification processes. It is not yet established which form of karstification was responsible for these features and also the South has been subdued to major uplift, which enhances later (meteoric) karstification processes. The nearby Variscan front might have been responsible for hydrothermal circulation and possible karstification. The North was subdues to a different tectonic and depositional regime and karstification processes might have been initiated by different factors. For now 2 theories can be conducted:

1. Karstification due to non-saline water input, after lithification. (uplift and/or lowstands).
2. Karstification along faults and/or fractures during hydrothermal circulation.

Theory 1 might be less likely, for if so UHM-02 would have encountered erosive surfaces. Theory 2 is possible probably to be found at slope deposits. Further research and more well information is necessary for solid conclusions, because diagenetic processes are extremely complicated and non-homogeneous. Especially when a large amount of time was available. Earlier karst features might have been cemented again at a later stage and also recrystallization processes might have taken place in multiple stages.

Reservoir types
The Petroplay project is a Joint Industry study conducted by TNO in 2004 and 2005. The main objective of the Petroplay project was to assess to petroleum geological potential of pre-Westphalian sediments in the Netherlands on- and offshore. Therefore this project contains valuable information on reservoir potential of the Dinantian carbonates onshore Northern Netherlands and will be discussed here. Presented in this project is a theory by Gutteridge (2002). Gutteridge (2002) gives an overview of potential onshore Dinantian reservoirs types associated with the Derbyshire UK carbonate platform, see figure 9. This could be an analogue for the carbonate build-ups found onshore Northern Netherlands.

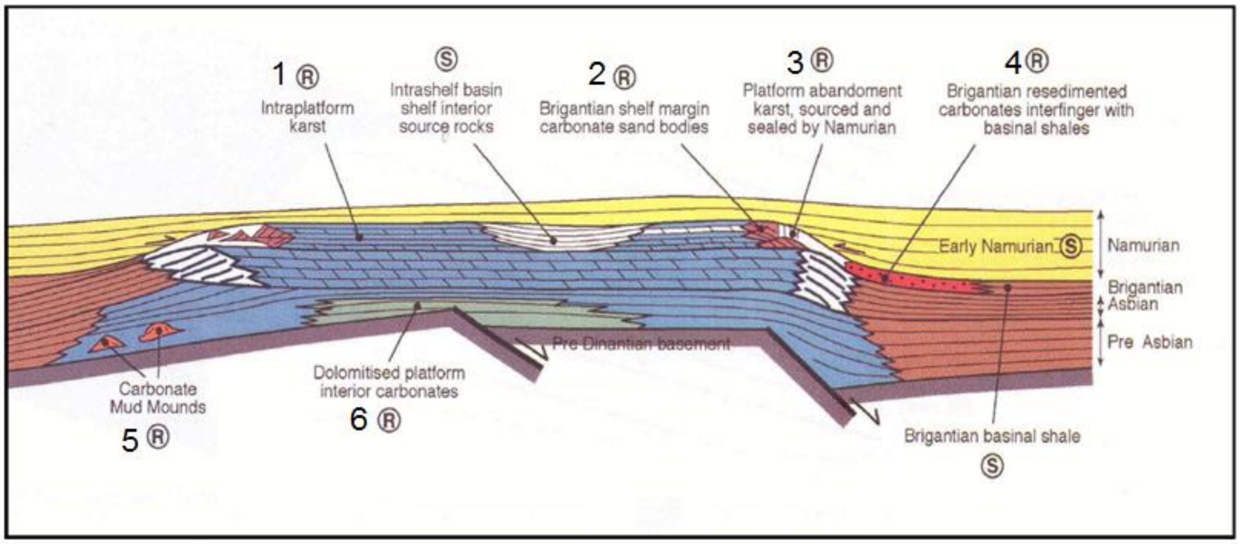


Fig. 11: Potential reservoirs and source rocks associated with the Derbyshire carbonate platform (from Gutteridge, 2002)

Potential reservoirs:

1) Intraplatform karst systems formed during eustatic sea level low stands. The pore system comprises channels and large vugs, superimposed on a moderate to poor matrix porosity representing relict depositional porosity. The reservoir is highly layered with karst systems extending few meters into the carbonate platform interbedded with impermeable shelf limestones. Brigantian time-equivalent.
2) Shelf margin bioclastic carbonate sand bodies occur at the shelf edge in a belt some 1-2 km wide. The width and thickness of these carbonate sand bodies is controlled by the relief on the carbonate platform margin. The carbonate sand body is layered at a scale of up to 15-20 m. These are separated by thin impermeable karsted and calcretised horizons. These carbonate sand bodies form a sheet draped over the base of the carbonate platform marginal slope and extend into the basin. Brigantian time-equivalent.
3) Carbonate platform karst reservoir type occurs at the carbonate platform margin and upper marginal slope. A dual porosity system is present (sub-vertical fractures superimposed on a matrix pore system comprising intergranular and occasional vuggy pores). Down-slope karstic collapse of the shelf margin has produced a boulder bed that contains large-scale channel and vuggy porosity. Brigantian time-equivalent
4) Post-platform karst systems formed after the cycle of basin development and sedimentation in which the Dinantian carbonate platform accumulated. Examples include sub Triassic and sub-Cretaceous karst. The pore system is a combination of high permeability fractures and large vugs, possibly up to several metres in diameter. Brigantian time-equivalent.

5) Carbonate mud mounds form potential reservoirs in the basinal parts. They form mounds, or bank-like features often up to several hundreds of metres thick and lateral spreads of several hundred metres to kilometres extent. Carbonate mud mounds are surrounded by flank facies comprising grainstone with good depositional porosity. Pre-Asbian time-equivalent.
6) Dolomitised platform interior carbonates. Dolomitisation took place in the presence of Mg-rich pore fluids expelled from surrounding shale-rich successions during Upper Carboniferous burial. Intercrystal porosity is moderate to good and borehole evidence shows that porosity is preserved in the subsurface. Pre-Asbian time-equivalent.

Potential reservoirs in the study area:

1) Possible, but not confirmed by well data.
2) Cannot be confirmed neither rejected by this study.
3) This type of reservoir might be present in the carbonate build-ups of the onshore Northern Netherlands, see chapter "Analogues" for further reading on this 4reservoir type.
4) Cannot be confirmed neither rejected by this study.
5) Cannot be confirmed neither rejected by this study.
6) Dolomite has been encountered in well UHM-02 and LTG-01, unfortunately they did not increase porosity and permeability.

In the chapter "Analogues", the seismic response of the Dinantian in the UK was discussed by Evans and Kirby (1999). Cores and cuttings of these build-ups have been compared to the seismic facies:

1. A 'stripy' facies with reflectors of moderate to high amplitude, corresponds to an alternating basinal (deeper-water) limestones and mudstones of the Worston Shale Group.
2. A 'quieter' with discontinuous low-amplitude reflectors, corresponds to a thick sequence of shallow-water platform carbonates overlying a thin and unbottomed series of clastic sediments."

(Evans and Kirby, 1999. And references therein)

LTG-01 is difficult to compare, for stratigraphy is hard to connect to the seismic response. UHM-02 has better ties to the seismic; the Zeeland formation represents the stripy facies and the Beveland member and Devonian are part of the quiet facies:

1. The Zeeland formation is described by Gutteridge as: deposition in open marine conditions episodes of relatively slow sedimentation. high-energy well reworked subtidal environment just above normal wave base, with intervals of a moderate to low energy subtidal environment just below normal wave base or in a sheltered subtidal setting within the carbonate sand body. The overall depositional setting was part of a carbonate shoal complex. Wave base is not a deep marine deposit, this does not correspond to the facies found by Evans and Kirby (1999).
2. Is the Beveland member consists of dolomite, which formed during a low stand (Van Hulten and Poty, 2008). The low stand represents shallow-water environment and the clastic input at the bottom of this member was interpreted as Top Devonian. This corresponds to the facies found by Evans and Kirby (1999).

From this it can be concluded that UK wells cannot be correlated 1 on 1 with the onshore Northern Netherlands carbonate build-ups and that information in reservoir quality has to be gained from elsewhere. For more information on reservoir quality see chapter: "Analogues".

Conclusion

Only 2 wells penetrated the Dinantian carbonate succession in the Northern onshore Netherlands: UHM-02 and LTG-01. LTG-01 does not contain late Visean (Asbian and Brigantian) deposits, UHM-02 on the other hand contains stratigraphy of the whole Visean. Both wells in comparison of the Southern onshore region miss the Tournaisian. There is no data supporting the timing of the other carbonate build-ups and whether the Beveland member (dolomite) is present in these areas. The Dinantian buildups encountered were, in general, deposited in a muddy environment with fine grained matrix with a lower initial reservoir quality. Also interbedded shale units found in LTG-01 and UHM-02 may form a baffle to vertical fluid flow. Because of the deep burial depth and diagenetic changes in the carbonates, the reservoir quality will be highly dependent on the secondary porosity developed through time: karstification, dolomitization and fracturing. UHM-02 and LTG-01 show signs of karstification (thin section scale). Dolomitization in these wells did not improve porosity and/or permeability. Karstification along faults and/or fractures during hydrothermal circulation is still a possibility, which is most likely to be found in slope deposits or near big faults. Diagenetic processes are extremely complicated and non-homogeneous. Especially when a large amount of time was available. Earlier karst features might have been cemented again at a later stage and also recrystallization processes might have taken place in multiple stages.

Geometry of the Dinantian carbonate build-ups in the Dutch Northern onshore

In this chapter, regardless of the carbonate depositional system, the term carbonate build-up is used to describe the process of carbonate accumulations. These carbonate build-ups result in different kind of geometries as presented in the chapter: ”Carbonate production and Dinantian carbonate precipitation”. Schlager (2005) states that build-up simply indicates that a carbonate body rose above the adjacent sea floor according to the principle of “ the rich get richer”. The term is unspecific about the origin of the carbonate material. It applies to a wide range of scales. The term has been used for features that are only a few meters in diameter and height, as well as for features measuring tens of kilometers across and over a kilometer in height. In this chapter each carbonate geometrie will be refered to as: “build-up”, identified on seismic profiles by way of onlapping reflectors.

This chapter discusses the results from seismic mapping of the reflector callibrated in wells UHM-02 and LTG-01, as top Dinantian, and subsequent time-depth conversion of this horizon. Seismic interpretation and time –depth conversion was done as described in the previous chapter: “methods, seismic interpretation and time-depth conversion”. The seismic mapping has lead to the identification of 4 build-up structures: Uithuizermeeden build-up, Fryslân build-up, Luttelgeest build-up, Muntendam build-up, see figure 1 for the TWT (ms) surface.

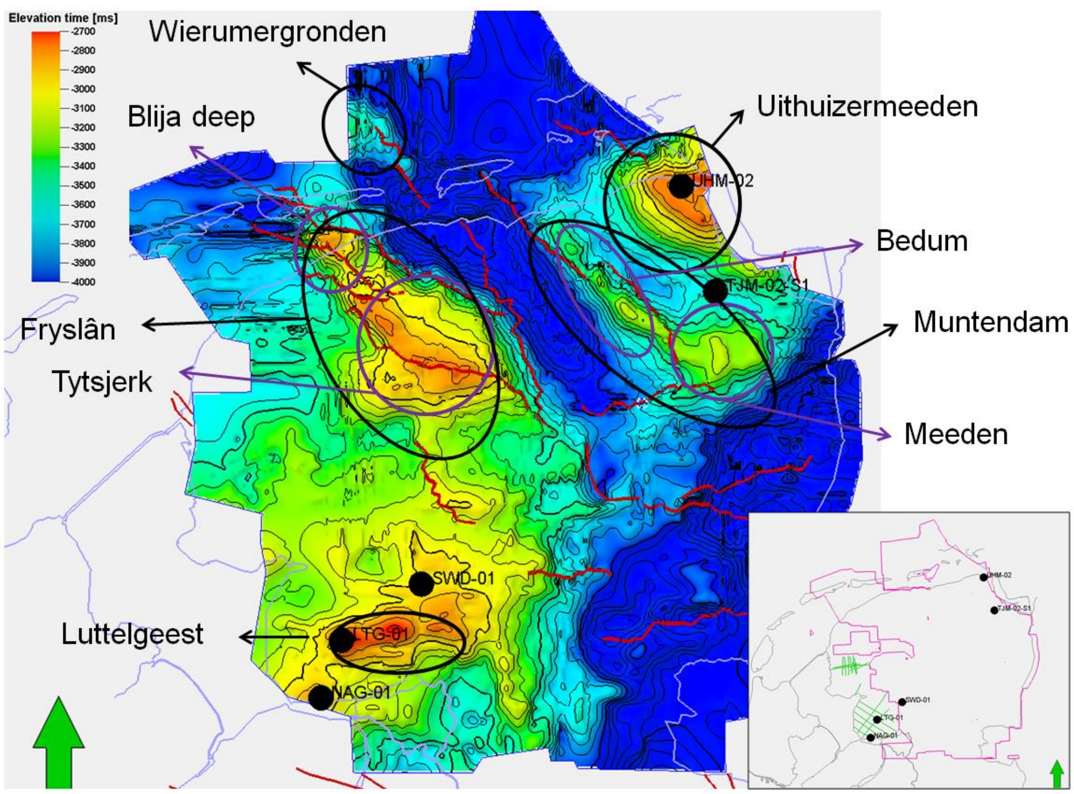


Fig. 1: TWT (ms) surface of the Top Dinantian. Blue is the deepest part, red is the shalloWest part. Red lines represent regional faults. Circles locate the identified build-ups.Black dots are the wels used for seismic interpretation. Wierumergronden is not mentioned in the text, because of great lack of seismic data, though the edge of a build-up can be recognised in this surface. The square indicates the outlines of the 3D (pink) and 2D (green)seismic data.

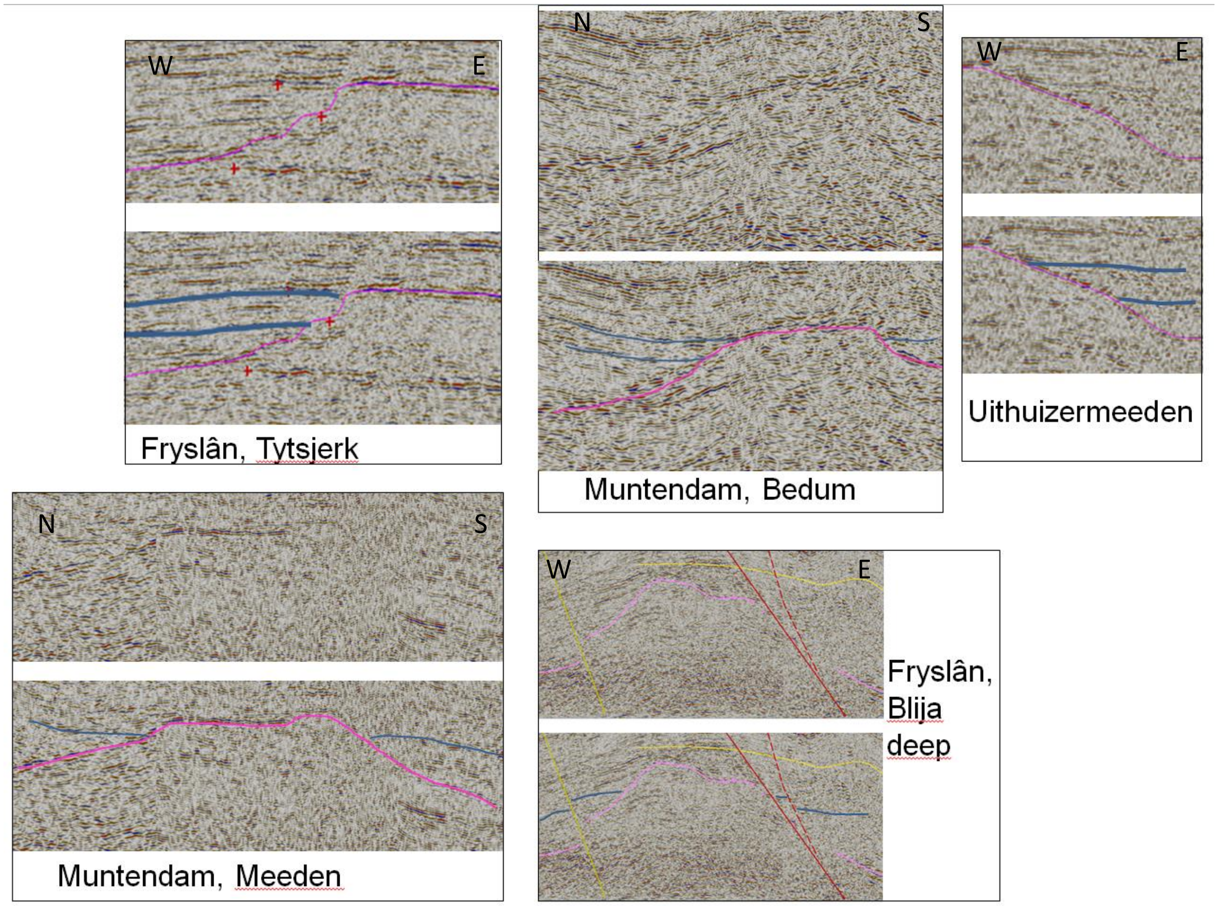


Fig. 2: Onlapping features which defined the outlines of the build-ups.

Because of significant differences in geometry, the build-ups can be further subdivided. Fryslân is subdivided in Blija deep and Tytsjerk. Whereas Blija deep seems to be isolated from the rest of the Fryslân build-up and bounded by faults. The Muntendam build-up is subdivided in Bedum and Meeden. The Bedum structure is a rim (purely meant as a geometrical identification; a rim need not be a reef) extending from the Meeden feature and surrounding the Uithuizermeeden build-up.

Although it might not be visible at each and every single in-and crossline, due to processing or local facies change, each build-up is strongly marked by onlapping features. Examples can be seen in figure 2. Seismic interpretation has been done in time, time-depth conversion is very arbitrary because of the limited well control. However I do realise that dipping events can change after converting the seismic to depth. The Zechtsein salt is very abundant in this area and might cause velocity pull up. However, I am describing the build-up geometries based on the time interpretation, strong reflectors and onlapping features can be recognized and mapped very well. As can be read in the chapter: ”methods, time-depth conversion”, the time-depth conversion is also subdued to several uncertainties and lack of data. Figure 10 shows the surface of the Top Dinantian after time-depth conversion; please note that geometries do not change significantly. Seismic conversion has not been carried out, for it would not improve the images. The geometries of the interpreted build-ups will be discussed here, a comparison with the Caspian Sea, UK and Cantabrian Mountains is discussed in the chapter: “Analogues”.

In this chapter each Build-up is illustrated with a seismic section.

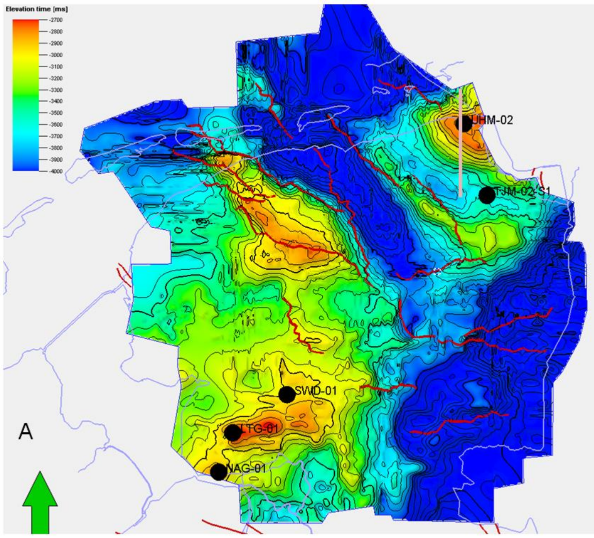
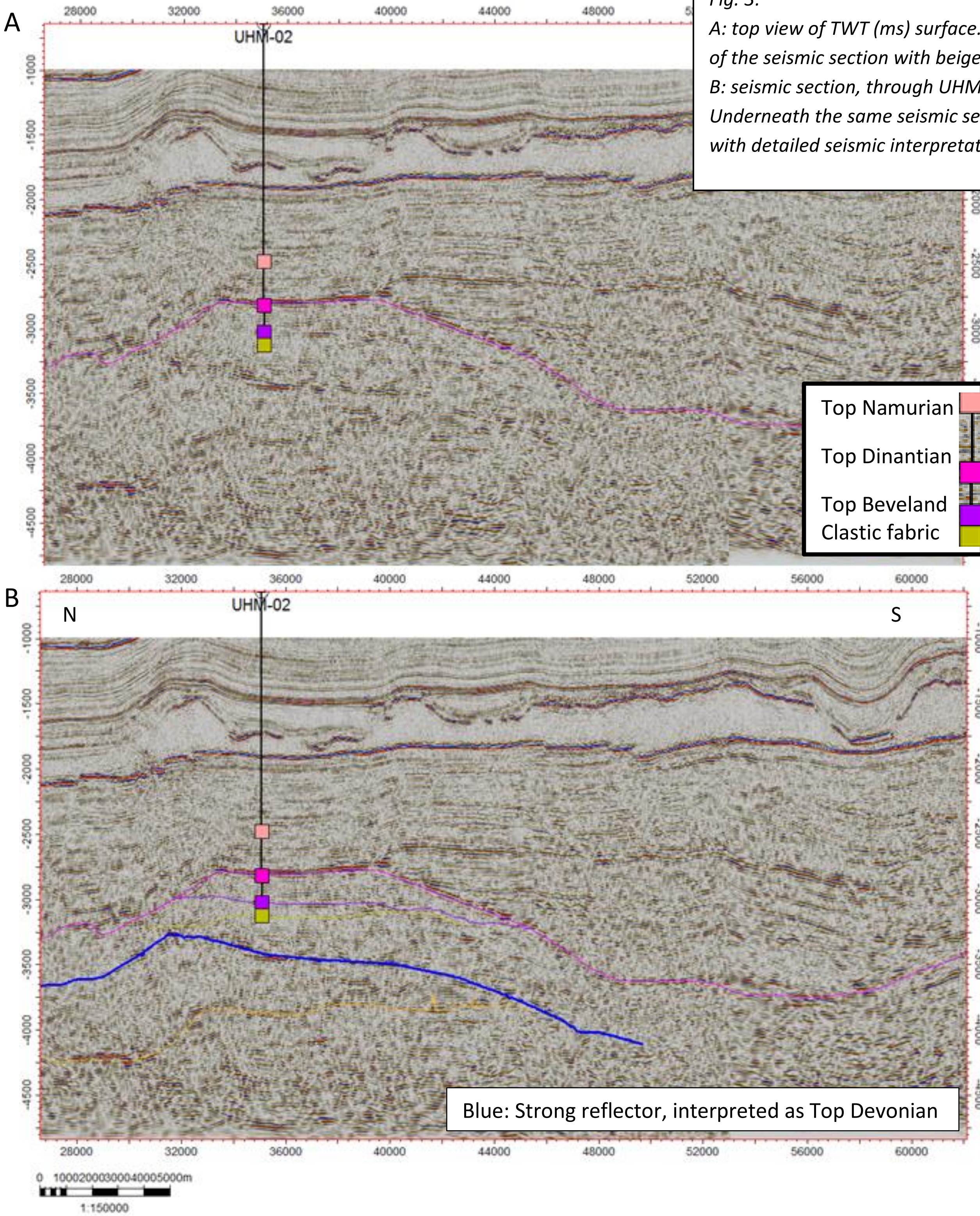


Fig. 3:
A: top view of TWT (ms) surface. Location of the seismic section with beige line.
B: seismic section, through UHM-02. Underneath the same seismic section with detailed seismic interpretation.

Uithuizermeeden build-up

The base of the build-up extends in a N-S direction for 21 km and W-E for 22 km. The base is recorded in the well UHM-02 by the well top; Top Devonian. This well top does not correspond with the strong reflector seen deeper in the seismic. Based on information from the operator, it is concluded that clastic intervals occur at the well top; Top Devonian. Although due to technical problems caused by high temperatures, the dating of these clastics remains uncertain. The clastic fabric could indicate reworked Dinantian deposits. A strong reflector near the supposed base of the build-up occurs at 3500 ms TWT (corresponding to approximately 6250 m). And from now on will be referred to as base of the build-up. The dimensions of this build-up are hard to constrain due to lack of seismic data at the German border. The flat top of the build-up has a radius approximately 7 km and occurs at 2800 ms TWT, corresponding to a depth of 4670 m. The Beveland member is encountered at 5130 m depth and it is possible a horizontal event, see figure 3B in the seismic section, at 3026 ms TWT. The Dinantian package is 660 m thick, divided in the Zeeland formation (450 m) and the Beveland member (210 m). Further away from the well the following formula is used to establish carbonate build-up thickness: base 6250m-top 4670m=thickness 1580m. The core of UHM-02, is described at the top as an high-energy reworked subtidal environment just above normal wave base, this environment is known to flatten carbonates build-ups. This build-up geometry can be referred to as a flat topped platform.

Fig. 3:
A: top view of TWT (ms) surface. Location of the seismic section with beige line.
B: seismic section, through UHM-02. Underneath the same seismic section with detailed seismic interpretation.



Fryslân build-up, Tytsjerk

This NW-SE trending build-up is bounded by faults. The top is flat and the base seems to be defined by a strong reflector underneath the build-up. The build-up seems to be tilted Eastward. The base is at 3300 ms TWT in the West and and 3700 ms TWT in East. Time-depth conversion results in a mean depth of 5600m at the base. The build-up base is 47 km long (N-S) and 28 km wide (W-E). Its culmination is at 2800 ms TWT and the lowest part is at 3150 ms TWT. Time-depth conversion results in a mean depth of 4300m at the top, resulting in a thickness of 1300m. At the top the build-up is 40 km long (N-S) and 4 km wide (W-E). The Southern part of this build-up is tilted towards the West. This build-up geometry can be referred to as a flat topped platform.

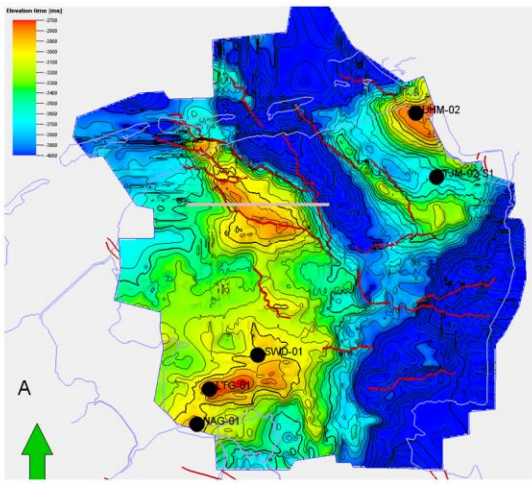
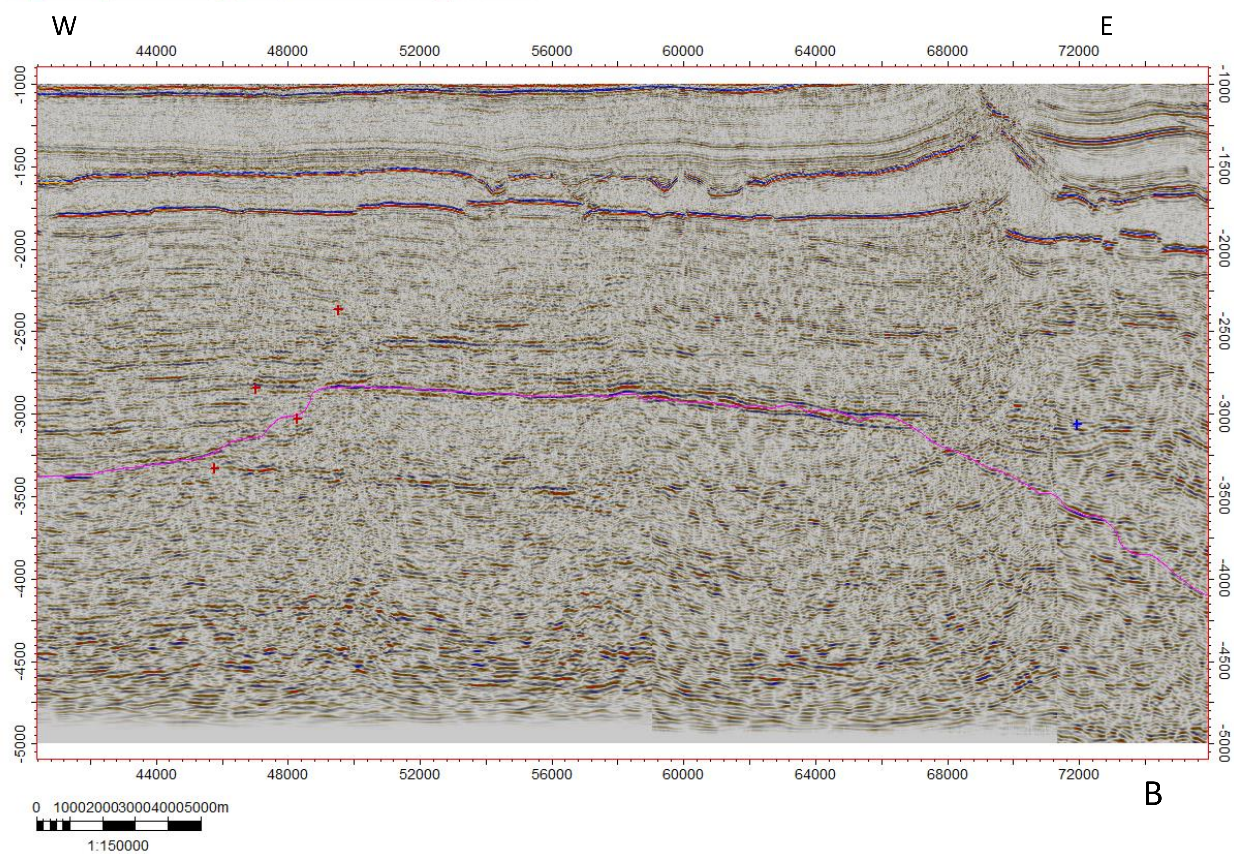
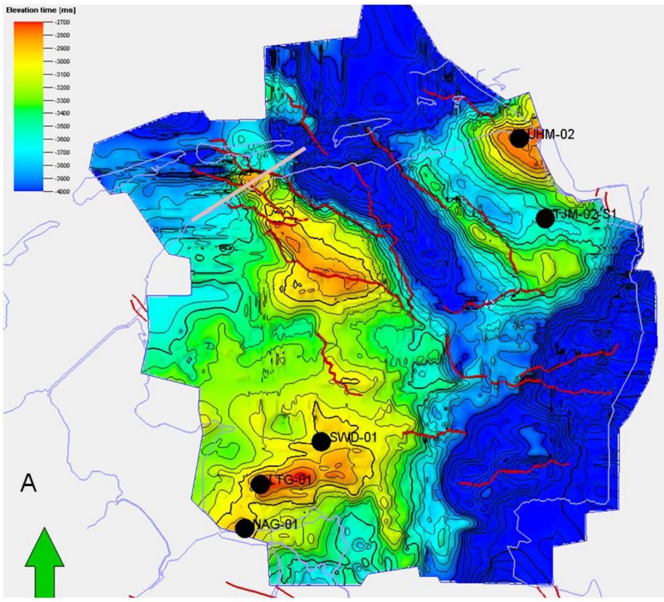


Fig. 4:
A: top view of TWT (ms) surface. Location of the seismic section with beige line.
B: West to East seismic section, through the Fryslân build-up, Tytsjerk part. The pink line is the interpreted Top Dinantian.



Fryslân, Blija deep

This build-up is part of the Fryslân build-up. It is bounded by steep dipping faults. Its slopes are much steeper than the rest of the Fryslân build-up. The base is identified by the strong reflector at around 3300ms TWT. Time-depth conversion results in a mean depth of 5600m at the base. The base has a radius of 7,5 km, the top is flat and dipping towards the NE. The top has a radius of approximately 4 km at 2800 ms TWT, and is also dipping in NE direction. Time-depth conversion results in a mean depth of 4300m at the top, resulting in a thickness of 1300m.The build-up is tilted in Northeastern direction. It seems that Blija deep is part of the flat topped platform of Tytsjerk, offset by faults.



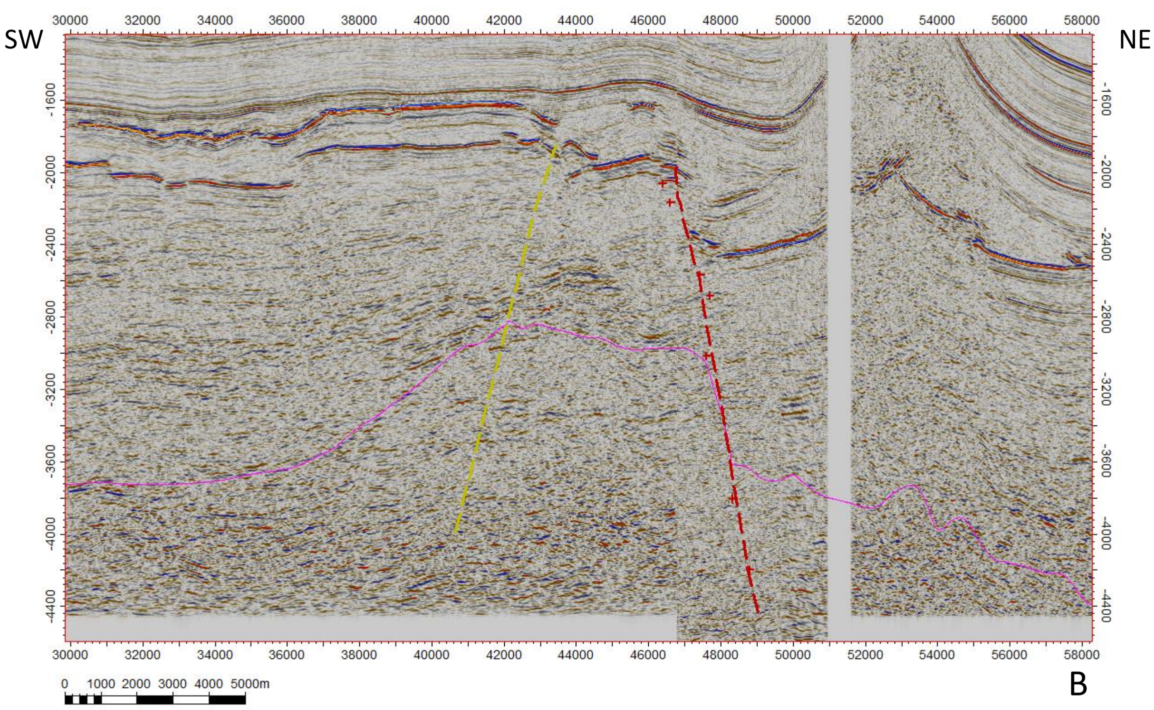


Fig. 5:
A: top view of TWT (ms) surface. Location of the seismic section with beige line.
B: SW-NE seismic section, through the Fryslân build-up, Blija deep part. The pink line is the interpreted Top Dinantian.

Luttelgeest build-up

This build-up trends in a W-E direction. The base is identified by a strong reflector underneath the build-up and it is defined by the well tops as Top Devonian. The base is flat , interpreted at 3000 ms TWT (corresponding to approximately 4850 m) and is 18 km long (W-E) and 7,5 km wide (N-S). The top is convex with flat intervals at 2700 ms TWT (corresponding to approximately 4300 m), and is 14 km long and 3 km wide. South-Westward extension of the build-up is unknown due to lack of seismic data. As can be seen on figure 1, this structure is mapped on seven 2D lines only. These lines cannot be connected to the 3D TerraCube seismic survey, therefore the outline of the structure is uncertain and mostly based on interpolation. The thickness of this build-up is 550 m. The geometry can be referred to as mound.

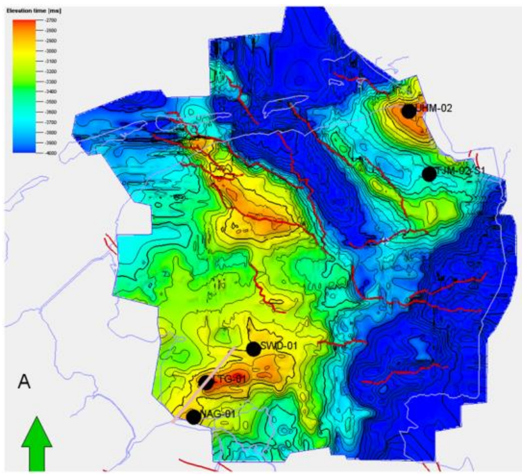
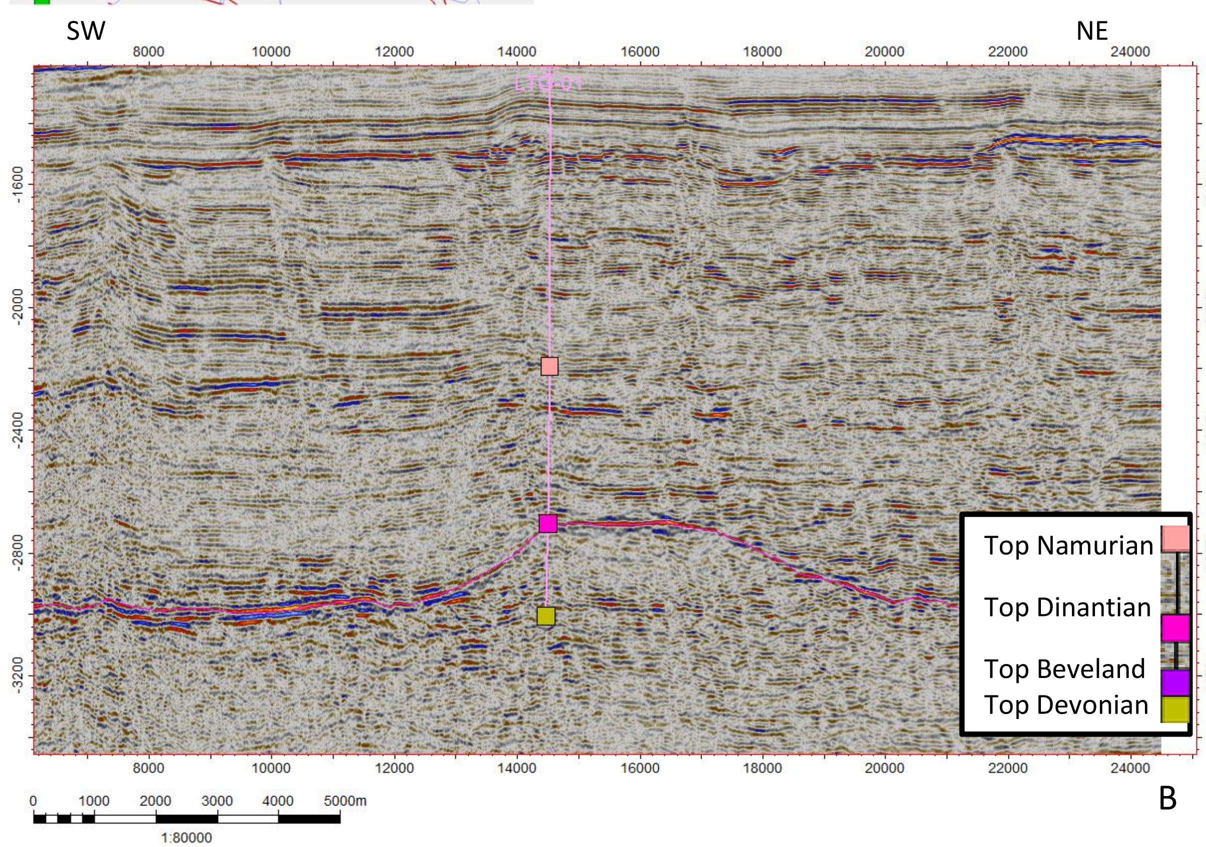


Fig. 6:
A: top view of TWT (ms) surface. Location of the seismic section with beige line.
B: seismic section, through LTG-01. Beige is Top Namurian, pink is Top Dinantian, and green is Top Devonian. The pink line is the interpreted Top Dinantian.



Muntendam build-up

This NW-SE trending build-up forms a rim structure around the Uithuizermeeden build-up. This build-up occurs deeper in time than the other build-ups and is, in contrast to the other build-ups, not flat. This is caused either due to it being a Devonian build-up or because of a paleotopography dipping plane. Figure 9C shows how mud mounds are not flattened by wave action, when they are created in deeper water on a dipping plane. The Build-up base is identified by a strong reflector underneath the build-up at 3500 ms TWT (corresponding to approximately 6600 m) and the base is 16 km long (N-S) and at least 20 km wide (W-E). The top varies around 3200 ms TWT (corresponding to approximately 5500 m), and it has a radius of approximately 14 km. The top is undulating or convex in geometry. The build-up has a rim that extends NW-wards around the Uithuizermeeden build-up. This “Bedum” extension is 32 km long and 4 km wide. The base, as identified by a strong reflector underneath it, is at 3800 ms TWT at the East side and at 4400 ms TWT at the West side. The top is not flat but round, with a maximum at 3300 ms TWT. Onlap is seen at both the East side as well as the West side. Between Uithuizermeeden and Bedum a deep is positioned at 4400 ms TWT. Both build-ups are approximately 1100m thick. The Muntendam build-ups refers to a mound geometry.

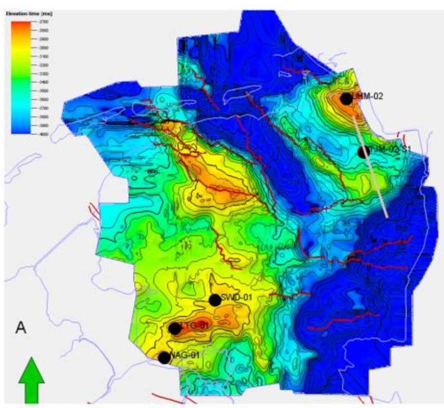
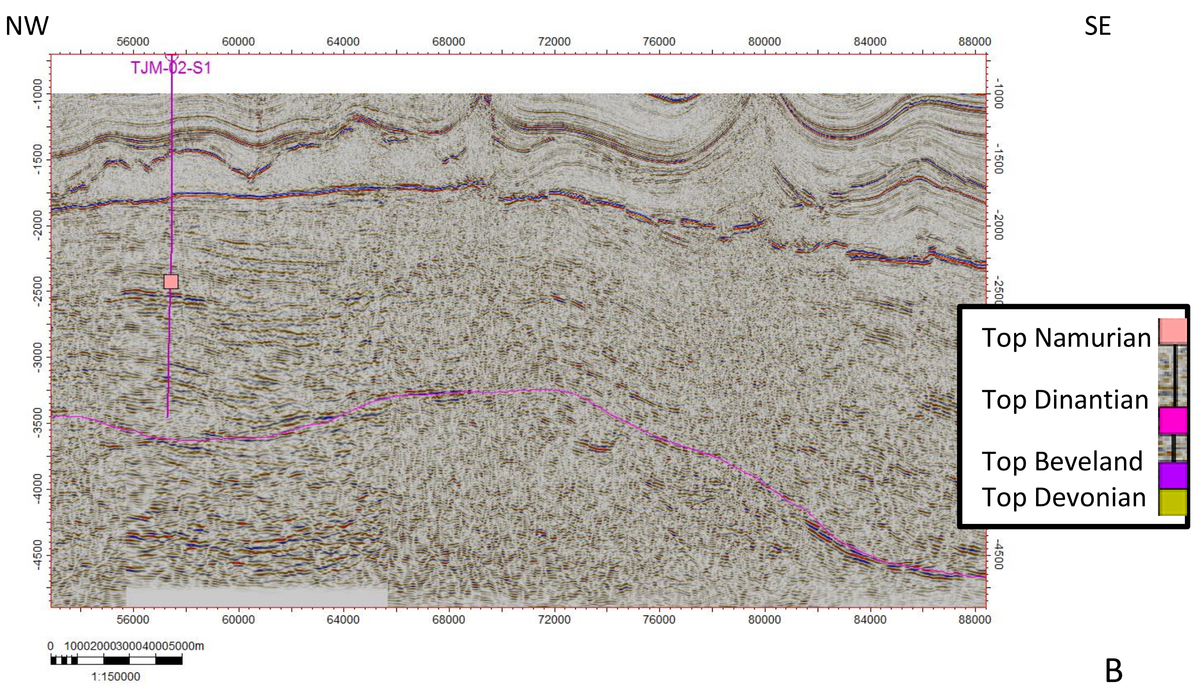


Fig. 7:
A: top view of TWT (ms) surface. Location of the seismic section with beige line.
B: seismic section, through TJM-02-S1. Beige is Top Namurian. The pink line is the interpreted Top Dinantian.



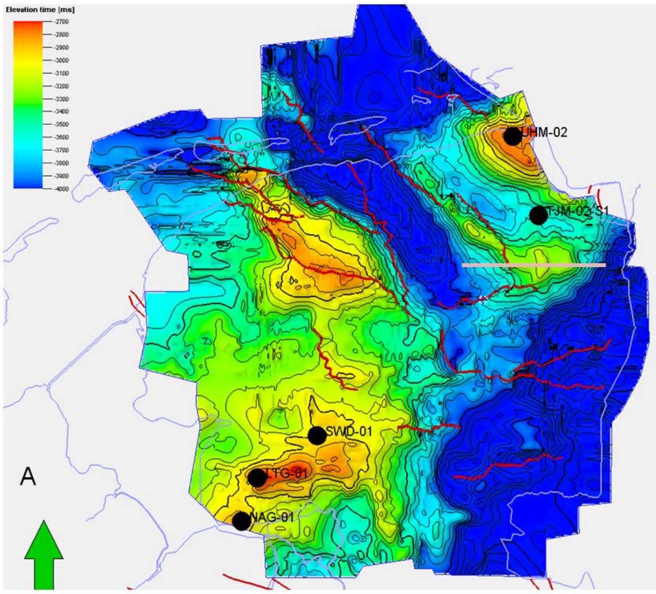


Fig. 8:
A: top view of TWT (ms) surface. Location of the seismic section with beige line.
B: seismic section, through UHM. Beige is Top Namurian, pink is Top Dinantian, and green is Top Devonian. The pink line is the interpreted Top Dinantian.

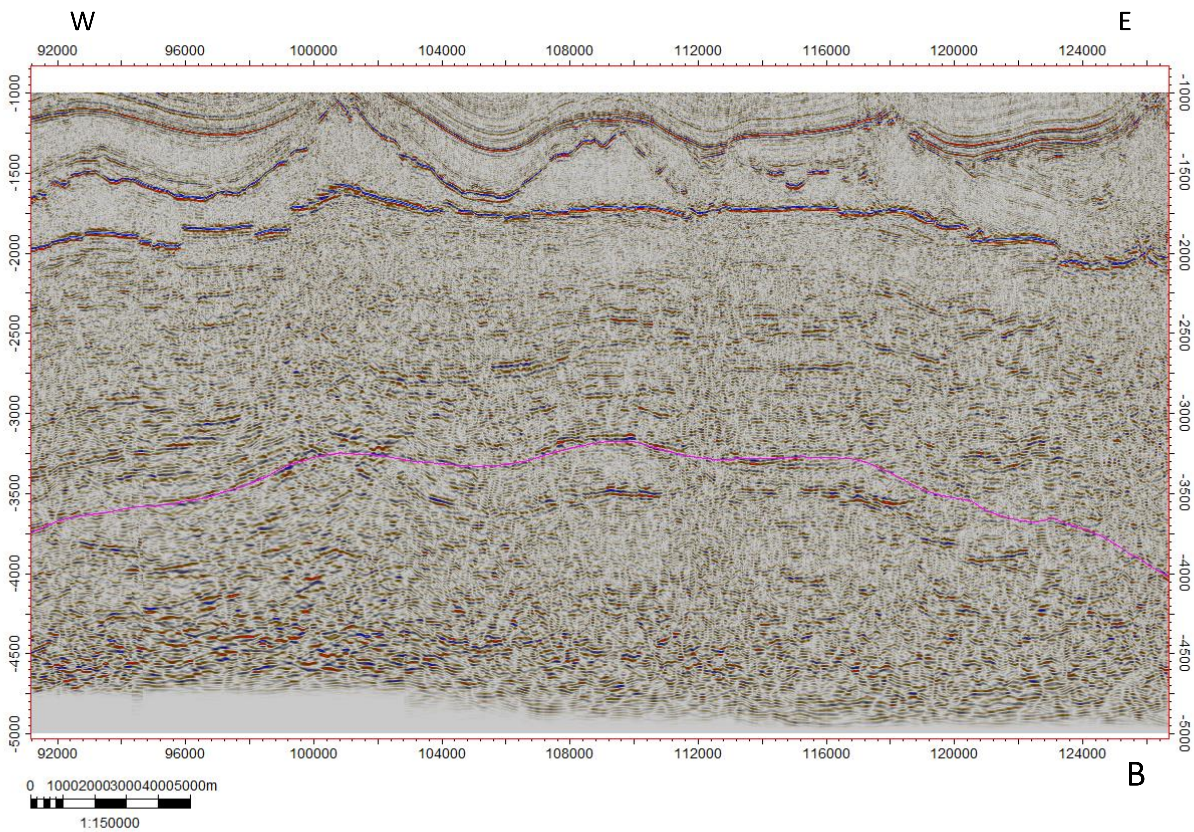


Figure 9 shows a seismic section through the Uithuizermeeden build-up, the Lauwerszee Through and the Fryslân build-up. The strong reflector associated with Top Devonian can be seen dipping towards the through at both sides. Whereas the (top of the) Uithuizermeeden build-up is horizontal , the top of the Fryslân build-up is tilted and the Bedum build-up is lower, smaller with a convex top. This demonstrates the theory of paleotopography forming shallow water mud mounds on the higher parts and deep water mud mounds on the lower parts due to a dipping event. Figure 9C shows how mud mounds are not flattened by wave action, when they are created in deeper water on a dipping plane.

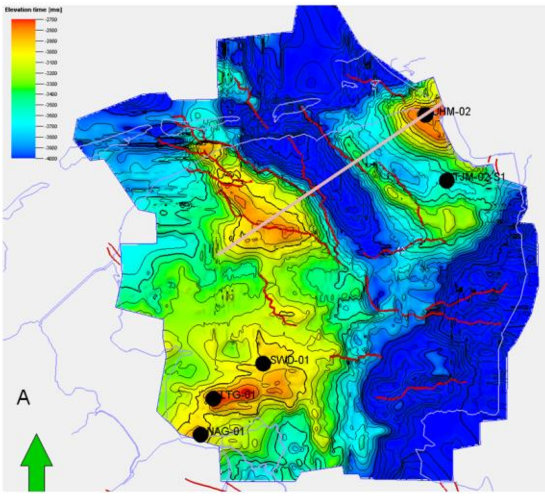
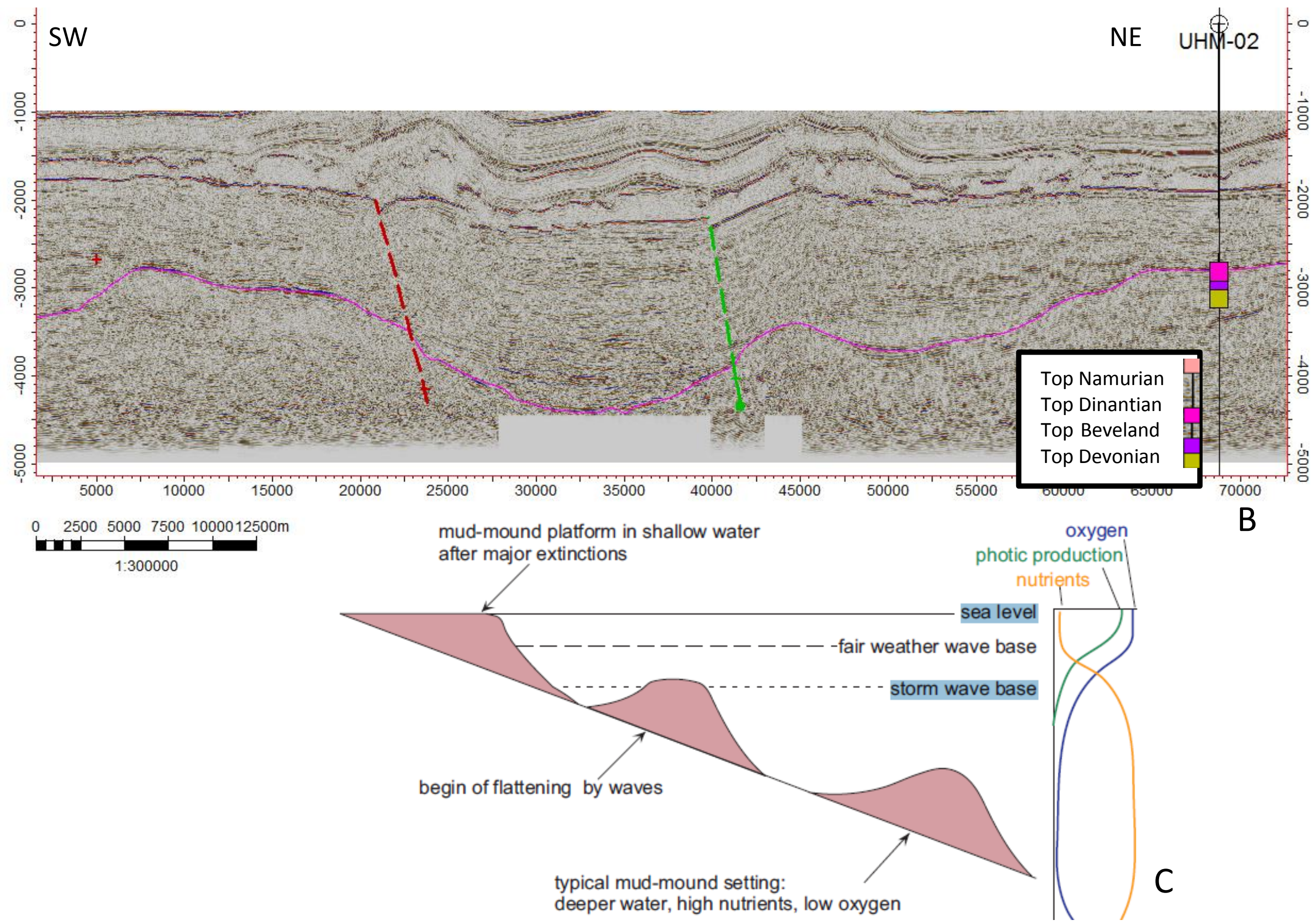


Fig. 9:
A: top view of TWT (ms) surface. Location of the seismic section with beige line.
B: seismic section, through UHM, Fryslân and the Lauwerszee through. Beige is Top Namurian, pink is Top Dinantian, and green is Top Devonian/Reworked Dinantian clastics. The pink line is the interpreted Top Dinantian.
C: Forming of mud mounds on a dipping plane: deeper water mud mounds are not flattened by wave action. After Schlager, 2005.



Uithuizermeeden	N-S	W-E
Build-up base depth	3500 ms TWT	3500 ms TWT
Build-up top depth	2800ms TWT	2800 ms TWT
Build-up base length	21 km	At least 20 km
Build-up top length	At least 7 km	At least 7 km
Base geometry	?	
Top geometry	Flat and horizontal	

Fryslân, Tytsjerk	N-S	W-E
Build-up base depth	3300-3700 ms TWT	3300-3700 ms TWT
Build-up top depth	2800-3150 ms TWT	2800-3150 ms TWT
Build-up base length	30 km	26 km
Build-up top length	24 km	15 km
Base geometry	Flat, dipping in Westward direction	
Top geometry	Flat, slightly dipping towards NE	

Fryslân, Blija deep	N-S	W-E
Build-up base depth	Around 3300 ms TWT	Around 3300 ms TWT
Build-up top depth	Around 2800 ms TWT	Around 2800 ms TWT
Build-up base length	7,5 km	7,5 km
Build-up top length	4 km	4 km
Base geometry	Flat and dipping towards the NE	
Top geometry	Flat and dipping towards the NE	

Luttelgeest	N-S	W-E
Build-up base depth	3000 ms TWT	3000 ms TWT
Build-up top depth	2700 ms TWT	2700 ms TWT
Build-up base length	7,5 km	20 km
Build-up top length	3 km	14 km
Base geometry	Flat	
Top geometry	Convex, with flat intervals,	

Muntendam, Meeden	N-S	W-E
Build-up base depth	3500 ms TWT	3500 ms TWT
Build-up top depth	Around 3200 ms TWT	Around 3200 ms TWT
Build-up base length	16 km	20 km
Build-up top length	10 km	13 km
Base geometry	?	
Top geometry	Undulating	

Muntendam, Bedum	N-S	W-E
Build-up base depth	3800-4400 ms TWT	3800-4400 ms TWT
Build-up top depth	Max. 3300 ms TWT	Max. 3300 ms TWT
Build-up base length	30 km	7,5 km
Base geometry	?	
Top geometry	Convex	

Table 1: Carbonate build-up geometries.

Conclusions

The Muntendam; Bedum build-up is deeper than the other build-ups; at least 300 ms TWT. Uithuizermeeden, Fryslân and Luttelgeest have flat (or flat intervals at the) tops, regardless whether this is due to erosion or sea level base, Muntendam on the other hand has an undulating top. The build-ups show no signs of reefs which is comparable to Dinantian carbonate build-up. There is a strong reflector present underneath each build-up. This reflector is not visible at each and every single in-and crossline, though this might be due to processing (the Terra cube comprises of multiple merged seismic surveys) or local facies change. For now the strong reflector will be referred to as Top Devonian, as recorded in LTG-01. As stated in the chapter “local geological history of the Dinantian onshore Netherlands”, the Dinantian build-ups were built on a dipping Devonian paleotopography (strong reflector), which could indicate either fault movement or Devonian reefs/build-ups. In case of clastics, which has a lower density than limestones, the acoustic impedance would be smaller than with limestones. Therefore the reflection co-efficient in the transition from Dinantian to limestones would give a stronger reflector than the reflection co-efficient in the transition from Dinantian to clastics. Also the transition from clastics to limestones underneath the Dinantian would be even more significant. This layer of clastics in between 2 carbonate build-ups might be the case at Uithuizermeeden.

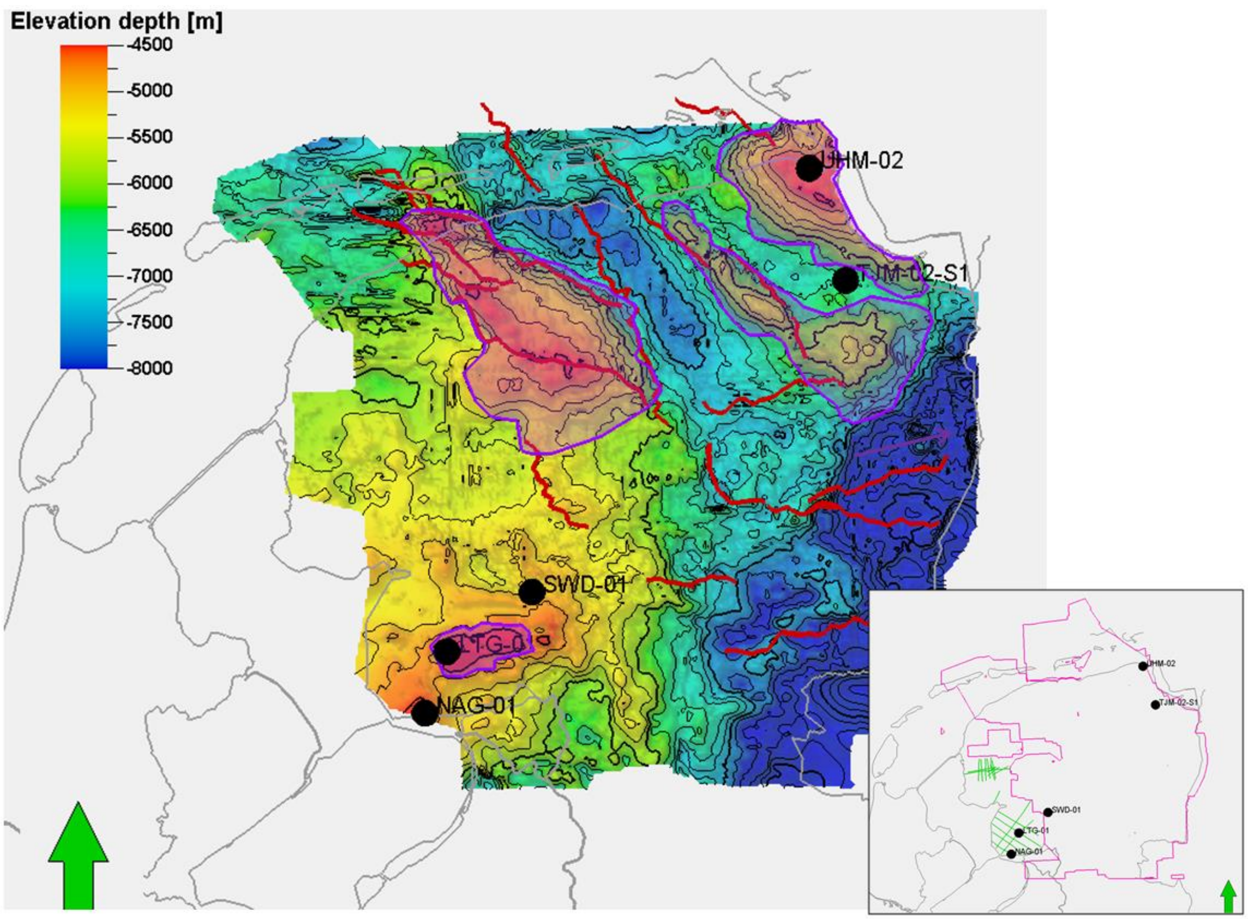


Fig. 10: Depth surface after time depth conversion. Countourlines at every 250 meter. Bold lines represent every 1000 meter starting from 5000 meter depth (or -5000 meter). Purple polygons represent the build-ups as found during seismic mapping by means of onlap, interpreted on TWT (ms).

Time-depth conversion as described in the previous chapter: "method, time-depth conversion", results in the following surface in meters, see figure 10.This depth surface has been used to make dip angle maps of the build-ups. The result of this can be seen in figure 11. The build-ups were cropped after careful outlining the onlapping features from the seismic. The resulting polygons can be seen on figure 10. Tables 2, 3 and 4 are the result of time depth conversion and geometry classification.

	Uithuizermeeden	Fryslân	Muntendam	Luttelgeest
Build-up base	6250 m	5600 m	6600 m	4850 m
Build-up top	4670 m	4300 m	5500 m	4300 m
Build-up thickness	1580 m	1300 m	1100 m	550 m
Build-up length	21 km	45 km	40 km	20 km
Build-up width	20 km	26 km	13 km and 7 km	7,5 km

Table 2: Carbonate build-up characteristics.

Geometry	Precipitation in	Appearance	Sequence	Observations
Platform	Shallow water	Flat top	Progradation	Rim present at Uithuizermeeden
Mound	Deep water	Convex	No progradation	Microbial origin
Ramp	Shallow water	~1,5° slope	No progradation	Seen North of the London-Brabant Massif
Reef	Shallow water	Framework	No progradation	No reefbuilders present in the Dinantian

Table 3: Geometry as defined by Schlager (2005).

	(Flat-topped) Platform	Mound
Uithuizermeeden	x	
Muntendam, Meeden		x
Muntendam, Bedum		x
Fryslân, Tytsjerk	x	
Fryslân, Blija	x	
Luttelgeest		x

Table 4: Carbonate build-up geometries in the study area as deduced from table 3.

Blija deep immediately attracts attention for the extremes in steepness. Note that the steepest events coincide with steep dipping faults with offset in the Dinantian. It is clearly visible that Uithuizermeeden and Tytsjerk have a flat top. Luttelgeest and Meeden have flat parts but are less uniform. The Fryslân build-up is inclined. Blija deep0 and Bedum are convex with steep slopes. The Luttelgeest build-up is much thinner than the Fryslân and Uithuizermeeden build-up. The chapter on well correlation states that Asbian and Brigantian are missing in LTG-01, therefore uplift and erosion must could have taken place at Luttelgeest. This will be further discussed in the chapter:" Local geological history of Dinantian onshore Northern Netherlands".

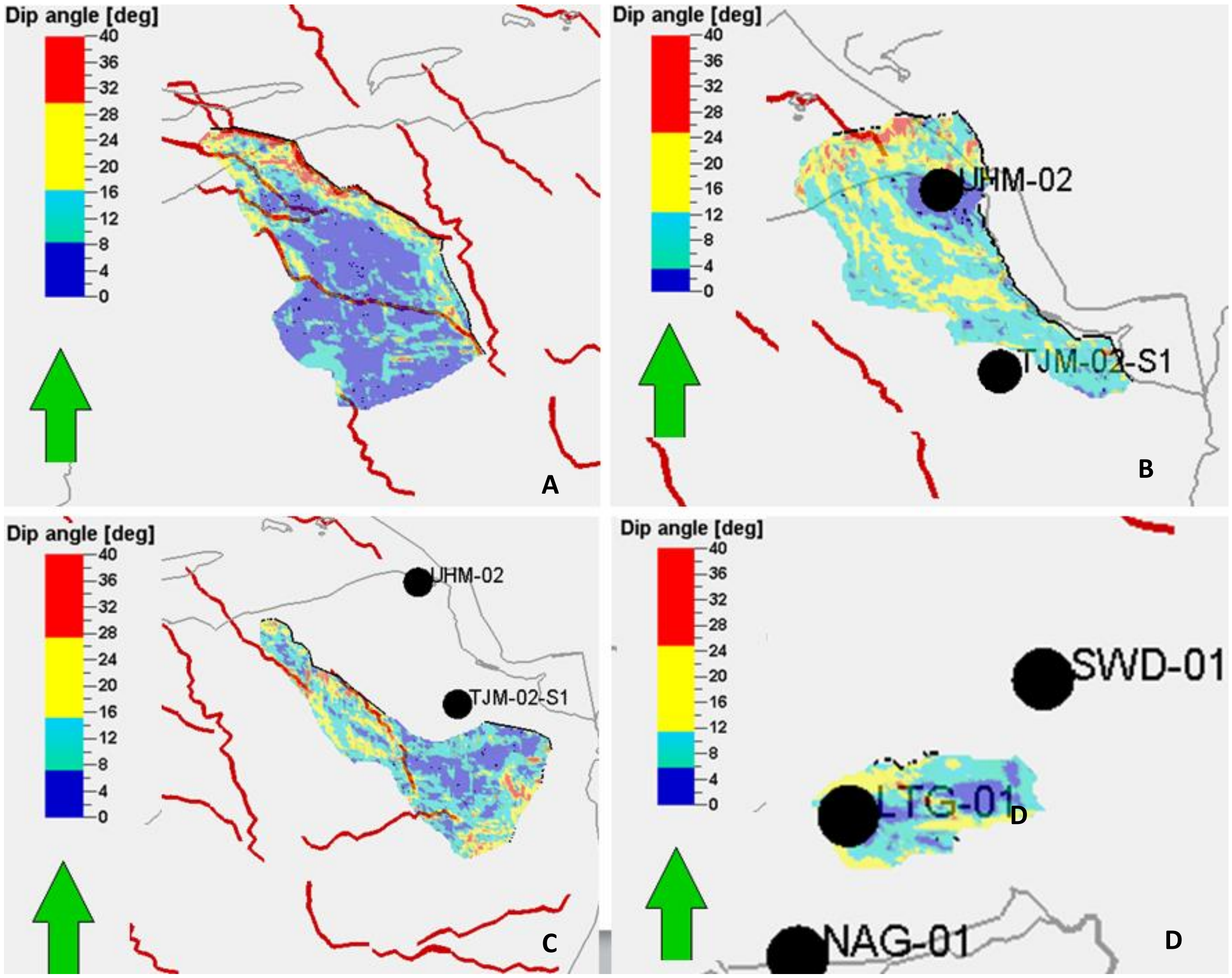


Fig. 11 A: dip angles of the build-up: Fryslan build-up, Fig. 11 B: dip angles of the build-up: Uithuizermeeden Fig. 11 C: dip angles of the build-up: Muntendam, Fig. 11 D: dip angles of the build-up: Luttelgeest. Red lines are faults and black dots represent wells.

The geological history of the Dinantian in the study area (Northern onshore Netherlands)

Introduction

At the end of the Ordovician, Avalonia and Baltica collided, followed by a collision with Laurentia during Silurian times. These three micro continents together are referred to as Laurussia. The Variscan orogeny started in late Devonian/early Carboniferous when Laurussia collided with Gondwana to form the supercontinent Pangea, this caused the closure of the Rheic Ocean. The suture between Gondwana and Laurussia is referred to as the Variscan front. The area of the Netherlands was located close to the triple-junction at some 40° to 30° South of the equator, see figure 1. During the Carboniferous, when Gondwana further encroached upon Laurussia, the front of the Variscan fold and thrust belt moved North, towards the Netherlands. Its final position runs approximately E-W through Belgium, just South of the Netherlands, swinging to the North-East into Germany (Ziegler, 1990). At that time, the Netherlands had moved to the Northern hemisphere, but still remained in the humid equatorial climate belt. (Geluk et al., 2007). Equatorial climates are commonly associated with warm, sunlit waters of the ocean that are high in oxygen because of constant equilibration with the atmosphere and low in nutrients because of intensive competition (Schlager, 2005).

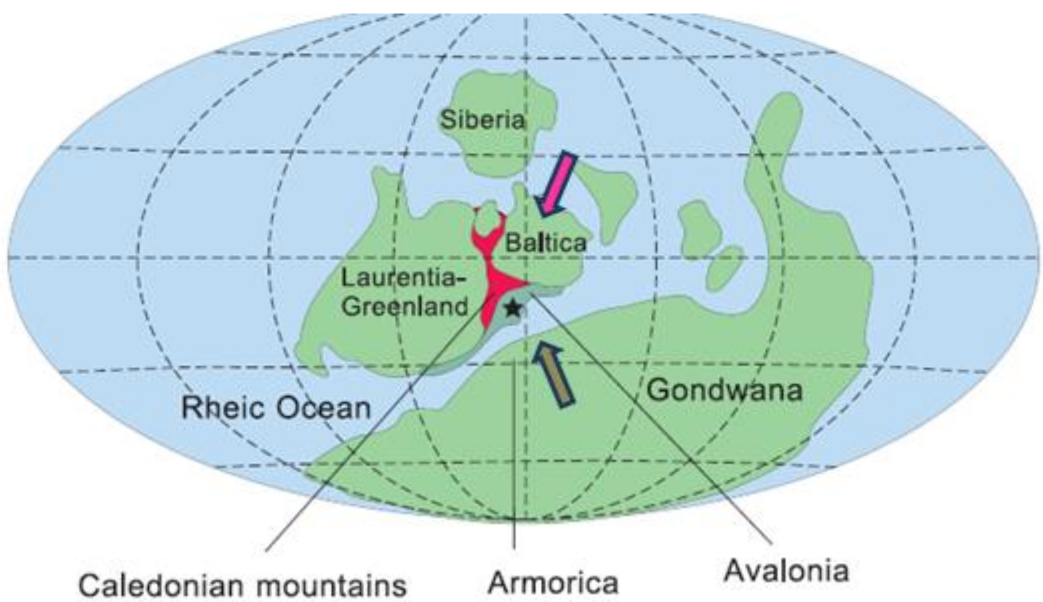


Fig. 1: Plate-tectonic reconstructions illustrating the Northward drift of Avalonia and its collision with Baltica and Laurentia. The star indicates the paleo-position of the Netherlands. Brown arrow indicates the supposed wind direction during Devonian times. The pink arrow indicates the supposed wind direction during Dinantian times. After (Geluk et al., 2007). Wind directions from Van Hulten (2012).

Biotically controlled precipitates dominate in such a climate, called the T factory. Most abundant among them are algae and animals with photosynthetic symbiotic algae. The T factory may also pass into the C(ool-water) factory downward in the water column, transitions from T to C factory occur in shallow tropical upwelling areas where cool, nutrient-rich water comes to the surface. After the severe extinctions in the Carboniferous, carbonate precipitation was dominated by algae, bryozoans and stromatoporids. These products are similar to the classical M(ound) factory. Mud mound build-ups can form flat topped platforms when flattened by wave action. (Schlager, 2005. And references therein). See chapter "Carbonate production, precipitation and geometries with a focus on the Dinantian", for more details on these carbonate factories.

The main structural features nowadays found in the Netherlands (see figure 2) find their origin related to the Caledonian orogeny (the NW-SE striking faults). One of the most striking features in the research area is the Lauwerszee Trough, this is a Northwest-trending sub-basin within the Southern Permian Basin and lies in the onshore area of Northeastern Netherlands. Less is known about the specific timing and induction of this feature, and this is discussed in detail below. Another important structural feature influencing the research area is the Texel-Ijsselmeer High. This is a NW-SE trending fault block, slightly dipping down to the Northeast. It affected sedimentation patterns and the structural development of the area from the Late Carboniferous-Early Permian to the Tertiary. The high influenced both the Permian facies distribution and the sedimentary processes during the Late Jurassic and the Early Cretaceous. Uplift of the high during the Late Jurassic and contemporaneous subsidence of adjacent basins can be linked with crustal extension. Late Jurassic faulting at the Southern edge of the high was accompanied by hanging-wall subsidence (Central Netherlands Basin) and footwall uplift (Texel-Ijsselmeer High and Friesland Platform). On both sides of the high, gas-producing Permian sandstones and carbonates have been found with good reservoir characteristics. Locally, Lower Cretaceous sandstones are gas-producing on the Friesland Platform. (Rijkers and Geluk, 1996. And references therein)

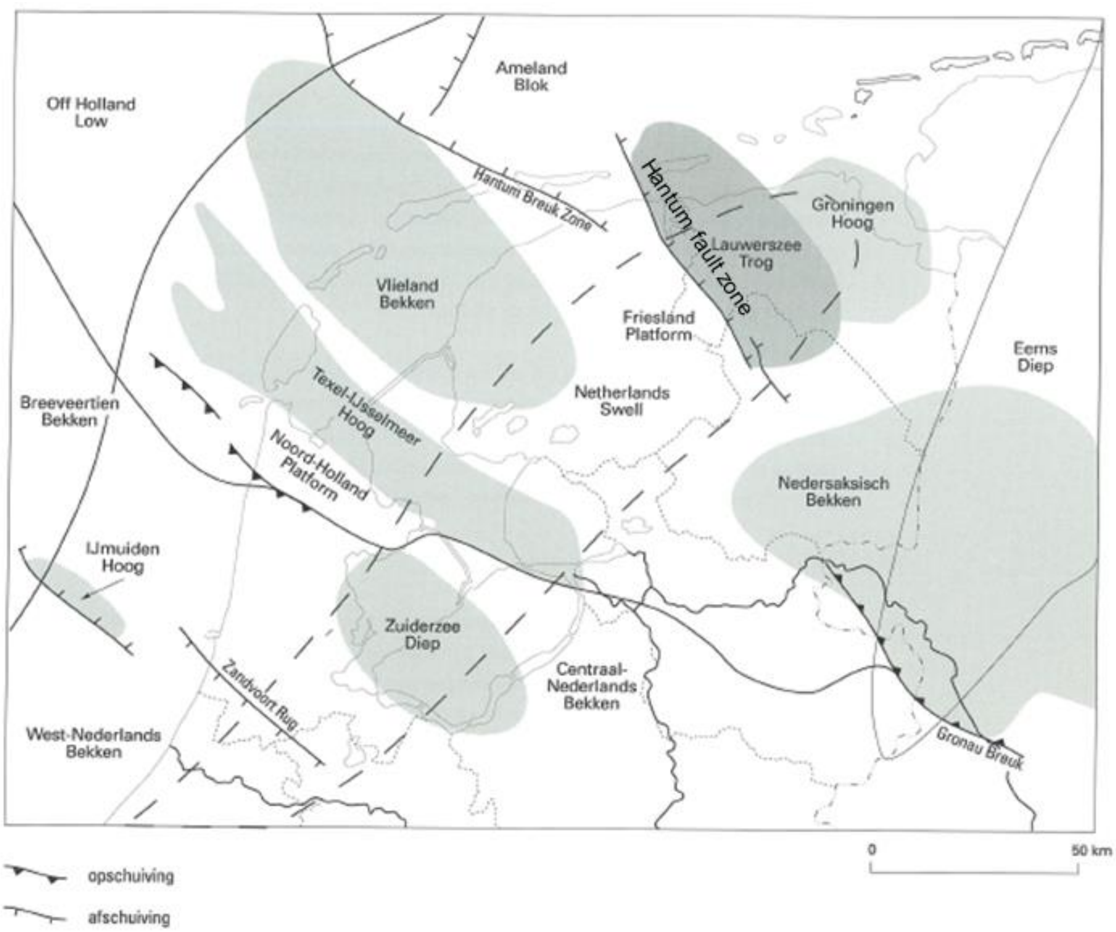


Fig. 2: Schematic overview of all relevant structural features in Netherlands. Map Sheets, from; http://www.nlog.nl/en/home/NLOGPortal.html.

The Lauwerszee Trough
4 carbonate build-ups have been identified in this study, see figure 3. Dinantian carbonate build-ups can form in extreme situations (for example in a situation depleted from sunlight), though commonly not deeper than 100m. No carbonate build-ups were found in the Lauwerszee Through, which indicates that it was already a deep during the Dinantian, or carbonate build-ups subsided due to faulting. Onlapping features, however, have been found at both ends of the deep, on the Fryslân, Uithuizermeeden and Muntendam carbonate build-up. Therefore implying no carbonate nucleation and accumulation took place in the deep. The Fryslân platform terminates to the South, wedging out. Further to the South the Luttelgeest carbonate build-up can be found. The geometry of the Luttelgeest platform and the termination of the Fryslân platform might be related to sediment influx from the Texel-Ijsselmeer High, the fault block, slightly tilted to the Northeast, affected sedimentation patterns of the area during the Late Carboniferous.

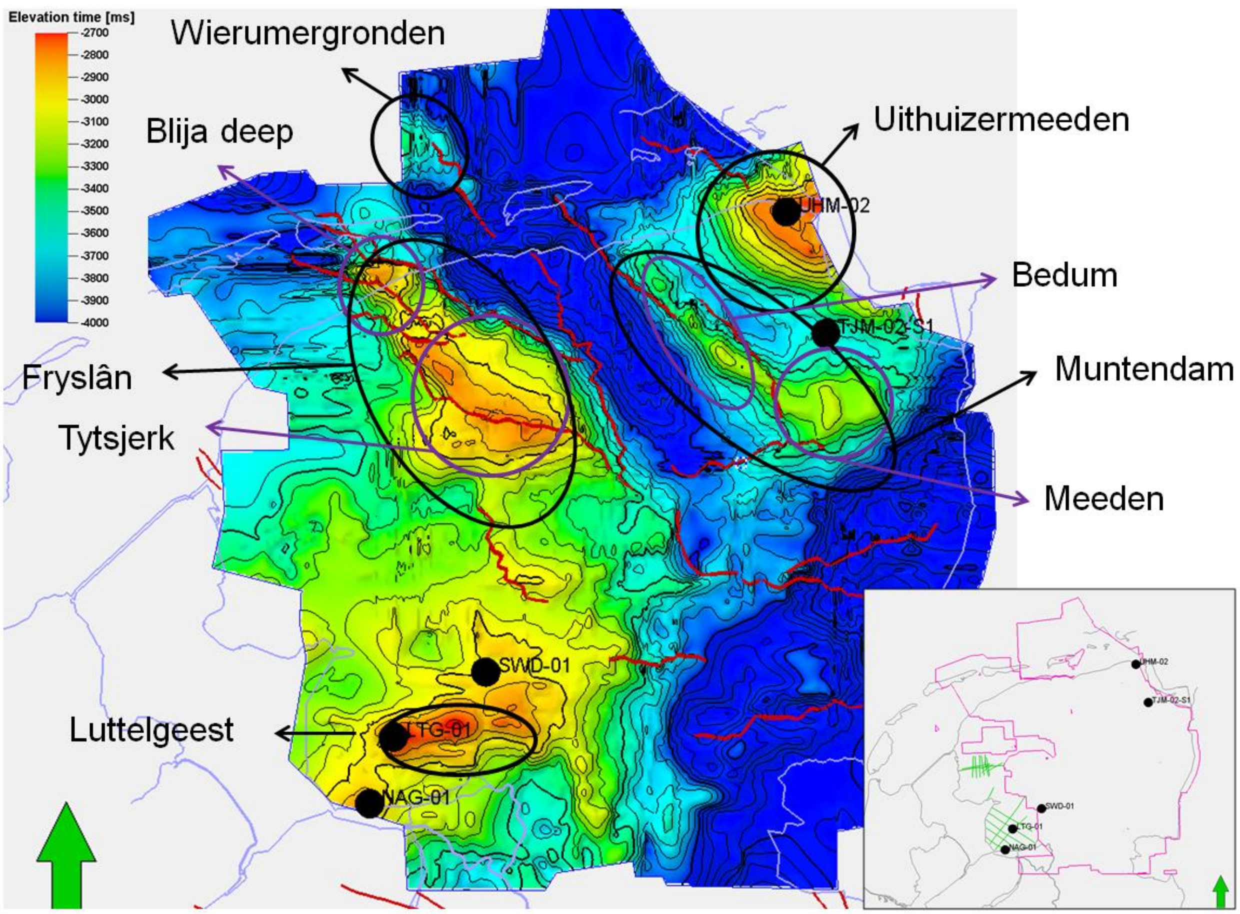


Fig. 3: *Surface of the horizon; Top Dinantian as interpretated on TWT (ms). Red lines are the interpretated faults and purple/black circles are the outline of the mapped carbonate build-ups. Small square represents the research area: Pink polygon is the outline of the 3D seismic data and the green lines are the 2D seismic lines.*

There are multiple explanations for the forming and timing of the Lauwerszee Through:

1. Structural; big graben. When a fault is active for a long period in time a big offset is expected. Especially the further down in the stratigraphy the bigger the expected offset, because the movement has been active for a longer period. This big offset is not supported by the seismic data (see figure 5). The top Dinantian horizon does not show big offsets

across the Lauwerszee Through faults. A possible explanation would be: ductile deformation, causing thinning of the Dinantian layer underneath the area marked as the Lauwerszee Through. High temperatures have been observed in well UHM-02 (see figure3 for the location). The temperatures recorded were 200°C at 5,3 km depth, resulting in a geothermal gradient of 37,7°C per km. The common mineral quartz makes a transition from brittle to ductile deformation at temperatures of roughly 350°C when water is present. Assuming a geothermal gradient of 30°C per km along an active plate boundary, then quartz-rich rocks will, fracture at depths above 11-12 km (=350 C/ 30°C per km), but will flow at lower depths, depending on the geothermal gradient that applies for a particular region. The Lauwerszee Through reaches a depth at Top Dinantian of 8 to 9km (see figure 4 for these depths). Calculating back: 8,5km *37,7°C per km = 320°C. Ductile deformation mechanisms are present in micrites between 200–300°C (Burkhard, 1990). From this, it is concluded that, ductile deformation at the Dinantian level in the Lauwerszee Trough, should not be excluded. This might explain the depth, seismic response and geometry of the deep.

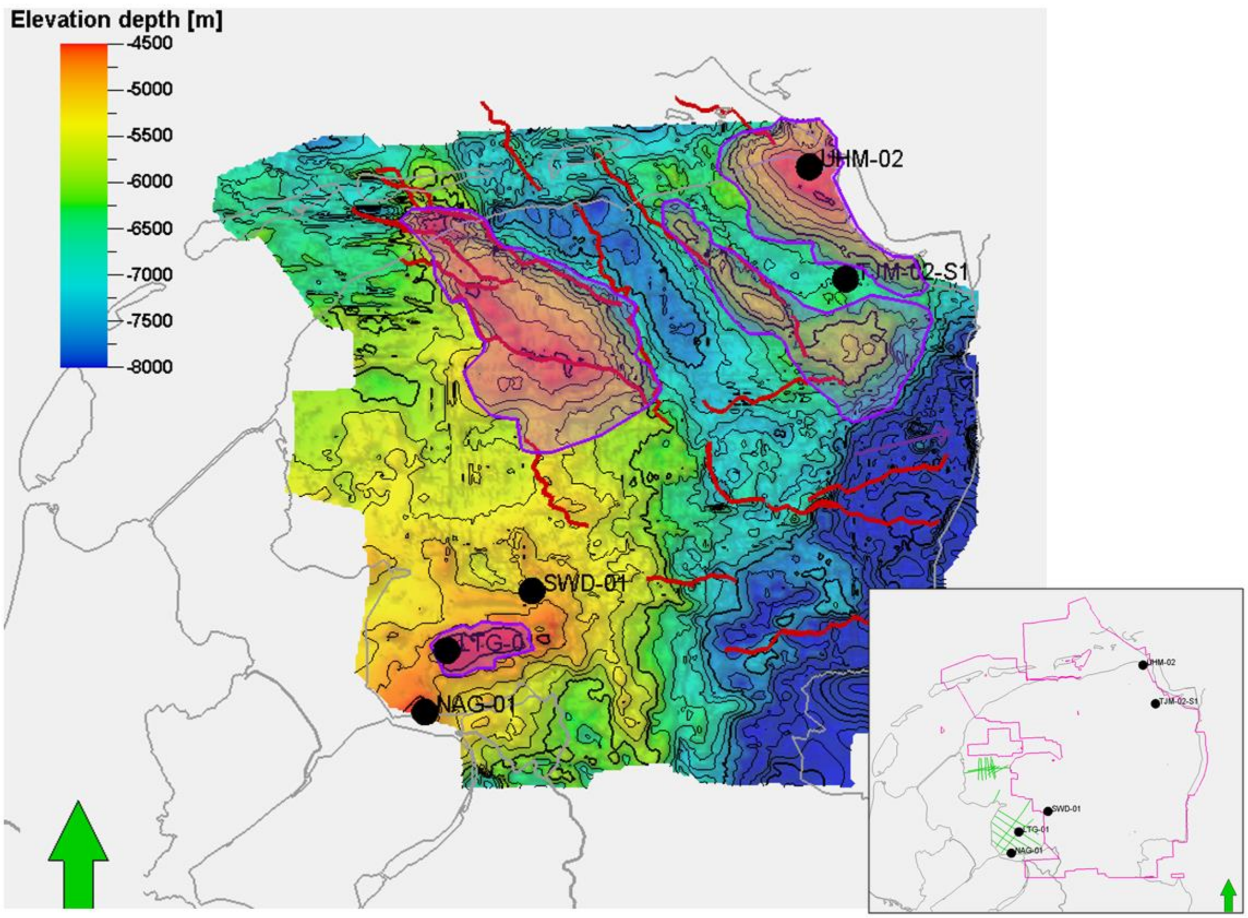
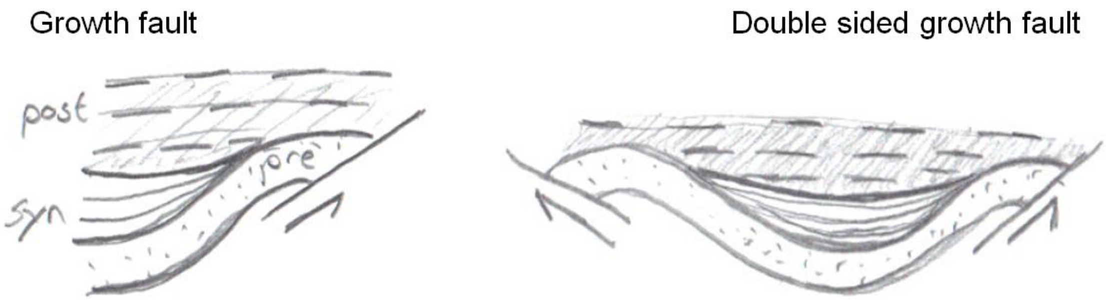


Fig. 4: Surface of the horizon; Top Dinantian after time depth conversion. Legend is in m depth. Red lines are the interpretated faults and purple polygons are the outline of the mapped carbonate build-ups. Small square represents the research area: Pink polygon is the outline of the 3D seismic data and the green lines are the 2D seismic lines.

2. Structural; double sided growth fault. As discussed above, the seismic does not show big offsets, see figure 5. A double sided growth fault (forming a syncline in between) could form a deep basin filled with marine deposits. This requires a thrust fault on both sides of this

growth fault syncline, see drawing 1 for the schematic overview of this theory. The East side of the Fryslân build-up shows faulting (see figure 5), though not retraceable throughout the whole study area. A thrust fault at the East side of the Lauwerszee Through cannot be confirmed for lack of seismic data at the German border. A theory that can be accepted for the time being.



Drawing 1: Schematic overview of growth faulting forming a deep. Left side: the forming of 1 growth fault. Right side the forming of 2 simultaneous growth faults

When the seismic section (figure 5) is flattened on the base Zechstein, the Lauwerszee Through is less deep, still forming a deepers tructure than the surroundings. Onlap is clearly seen at the surrounding carbonate build-ups, confirming Bedum as a pronounced carbonate build-up, not a pull up structure due to faulting. The Hantum fault zone is not causing the tilting of the Fryslân build-up, for it is still tilted after flattening. Tilting is probably due to an uplift factor from the Southwest.

As seen in figure 5 the Fryslân carbonate build-up is tilted. The surface maps (figure 3 and 4) shows a shallower topography of Top Dinantian in the Southwestern section of the research area. The Luttelgeest build-up is missing Asbian and Brigantian, possibly caused by erosion. All give rise to the idea that the Southwestern section of the research area has been uplifted. Alternatively, the Luttelgeest build-up might have been drowned earlier than the Fryslân build-up because of the "Steepen the slopes" principal. Carbonate slopes steepen with height and are generally steeper than slopes of clastic accumulations. Slope lithification retards slumping and stabilizes steep angles once they are formed, this limits the growth of the carbonates and the mud-mound is drowned (Schlager, 2005 or see chapter "Carbonate production, precipitation and geometries with a focus on the Dinantian", for more details). Luttelgeest may not have been subdued to erosion. This does not exclude uplift however. De Jager (2007) states that, the Texel-Ijsselmeer High was part of a larger E-W running uplifted zone. Uplift probably took place after the Westphalian A, for it is subcropping in the Southwest of the research area (see figure 9) and the Westphalian B and C is eroded.

"Early Carboniferous tectonic extension reactivated the NW-SE trending zones of weakness, which had been inherited from the Caledonian orogeny. Asymmetric grabens were formed, resulting in the trends of the major Dutch structural elements onshore like the Texel-Ijsselmeer High and the Lauwerszee Trough (along the Hantum fault zone). At the close of the Carboniferous, the area of western Europe became affected by late-Variscan post-orogenic tectonism. Wrench faulting and thermal uplift caused widespread and deep erosion. The Lauwerszee Trough is an area that experienced less uplift and erosion. The Texel-Ijsselmeer High was part of a large uplifted zone. The major Hantum fault zone at the western margin of the Lauwerszee Trough was active at this time, juxtaposing Westphalian B and C against Westphalian A. "(Van Buggenum and Den Hartog Jager, 2007. And references therein).

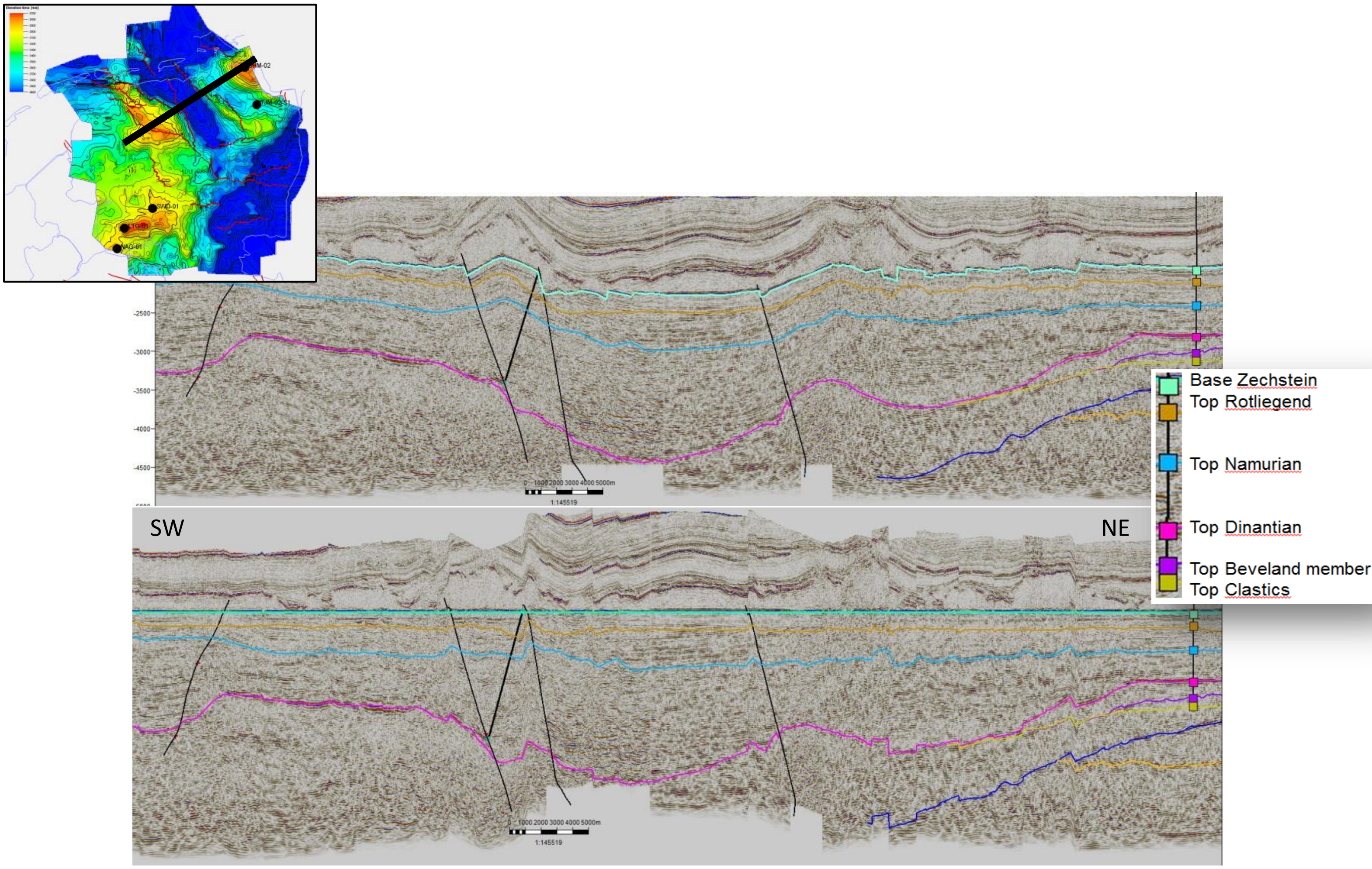
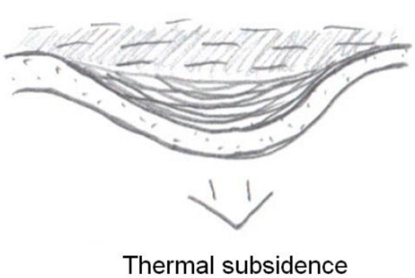


Fig. 5: Seismic section through Uithuizermeeden, Muntendam and Fryslân. Mapped faults in black. Small square is outline of the research area and emplacement of the seismic section. Top seismic section is in ms TWT, bottom seismic section is flattened on base Zechstein.

3. Structural; thermal subsidence/ thermal sag basin (see drawing 2). “Modern” examples of intra-cratonic sag basins include the slowly subsiding, continental Chad basin in Northern central Afrika and the Eyre basin in Australia. The crustal processes forming these basins are not well understood. Most basins lack major extensional faulting, apart from early rifting as observed in many cases. Thus, log-term thermal contraction and/or eclogitization of the lowermost crust, or intraplate stress seem to be the major mechanism in generating subsidence (Einsele, 2000). The geometry of the Lauwerszee Through might look like a thermal sag, however the small dimensions do not suit the criteria. Also the uplift in the Southwest as stated in literature does not support this theory. Therefore this theory is considered unrealistic.



Drawing 2: Schematic overview of thermal subsidence forming a deep.

Devonian Paleotopography

The total succession of the Fryslân build-up has been tilted, its base: Top Devonian, therefore also experienced uplift. This suggests that the Top Devonian was a horizontal structure in the Southwest of the research area, before it was lifted up. Top Devonian in the Northeast of the research area is dipping towards the SW, towards the deep (see figure 5). There are several theories on how the Top Devonian formed its paleotopography, these theories are discussed below.

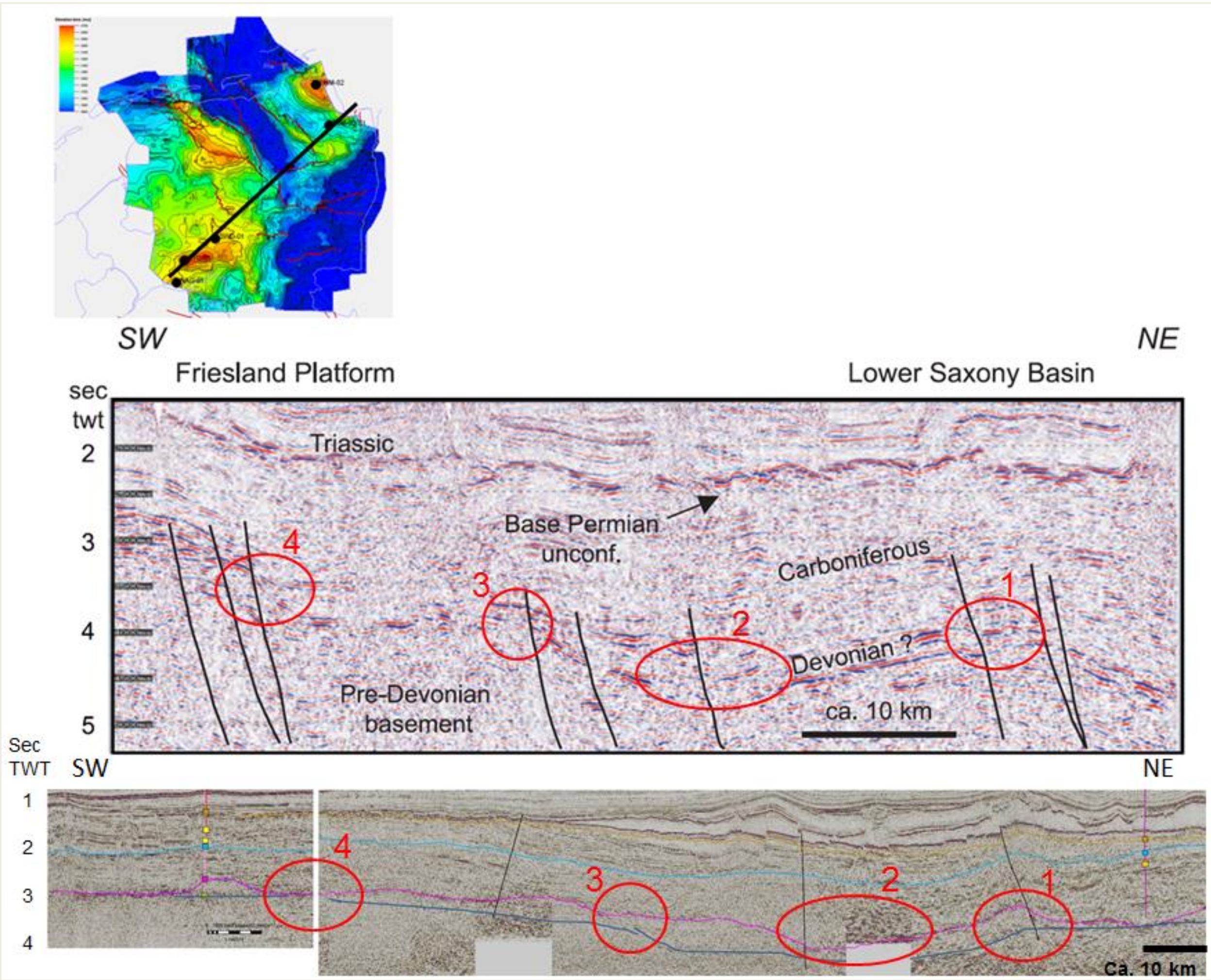


Fig. 6: Above; a seismic section through Muntendam and Luttelgeest (De Jager, 2007). Black are the mapped faults. Small square is outline of the research area and emplacement of the seismic section. Underneath a seismic section reconstructed from 3D and 2D seismic. Pink is the Top Dinantian as interpreted in TWT (ms). Blue is Top Devonian as interpreted. Small square is outline of the research area and emplacement of the seismic section. Left is the well LTG-01 and right is the well TJM-02-S1.Red circles indicate similarities recognized in seismic.

1. Fault blocks theory: The seismic section in figure 6 (underneath) is based on a 2D line in the SW part and a 3D seismic random line in the NE part of the study area. The line is taken through 2 wells. The seismic section of figure 6 (above) is a long 'old' 2D line that lacks well control. Several similarities are recognized; the tilted Devonian in the NE (1), the deep in between (2), which represents the Lauwerszee Through and the higher position of both the Dinantian and the Devonian (3 and 4). Faults have been interpretated in this study (figure 6 underth), although non

of with offsets lower than Dinantian. This theory/interpretation is an ambitious one, but plausible.

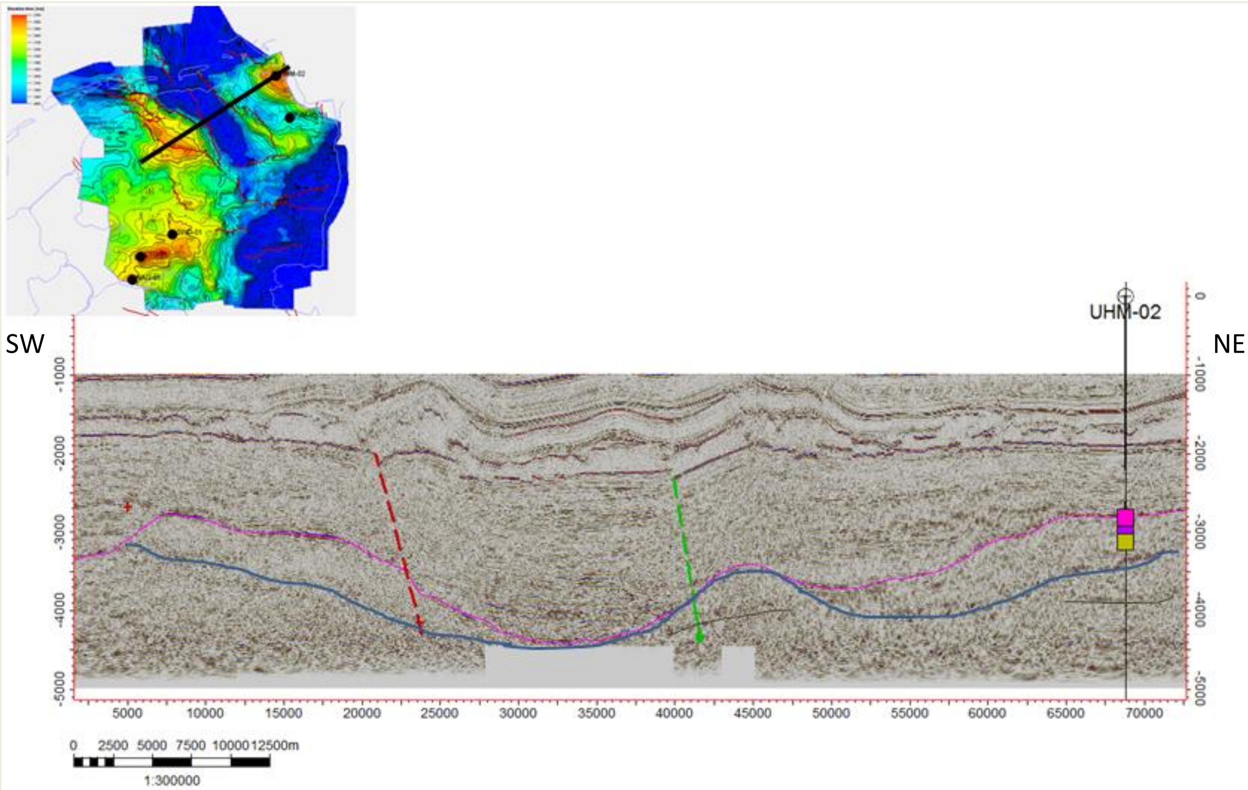


Fig. 7: Seismic section through Uithuizermeeden, Muntendam and Fryslân. Green and red lines are 2 of the mapped faults. Pink is the Top Dinantian as interpreted in TWT (ms). Blue is Top Devonian as interpreted. Small square is outline of the research area and emplacement of the seismic section.

2. Devonian platform theory: The strong reflector found underneath the Dinantian carbonate build-ups, classified earlier as top Devonian (not confirmed by well data) can be traced from the Uithuizermeeden build-up through the Muntendam build-up to the Fryslân build-up. See figure 7 for a reconstruction of this interpretation. Van Hulten states that the Muntendam build-up is of Devonian age. The wind direction in Devonian times is believed to have been South-Southeast (Van Hulten, 2012), bringing in nutrients and favoring Muntendam for carbonate growth. In Dinantian times wind direction is believed to have come from the North-Northeast (see figure 1), changing nutrients influx and favoring Fryslân and Uithuizermeeden for carbonate build-up growth. This results in the drowning of the Muntendam build-up and Fryslân and Uithuizermeeden build-ups. Seismic data supports this theory (see figure 7), where top Devonian can be traced. The Devonian build-ups are drowned and are used to nucleate Dinantian build-ups, whereas the Muntendam build-up gets less influx of nutrients. Although interpretation of a reflector this deep is extremely hard. The Luttelgeest build-up would also have been in a good position for Devonian carbonate accumulations. Luttelgeest is thinner (see figure 4) just as Muntendam, both have a geometry of convex tops with flat intervals. Luttelgeest has been drilled and proven to be a Dinantian carbonate build-up. Therefore the Muntendam build-up can still be thought of as a Dinantian carbonate build-up.

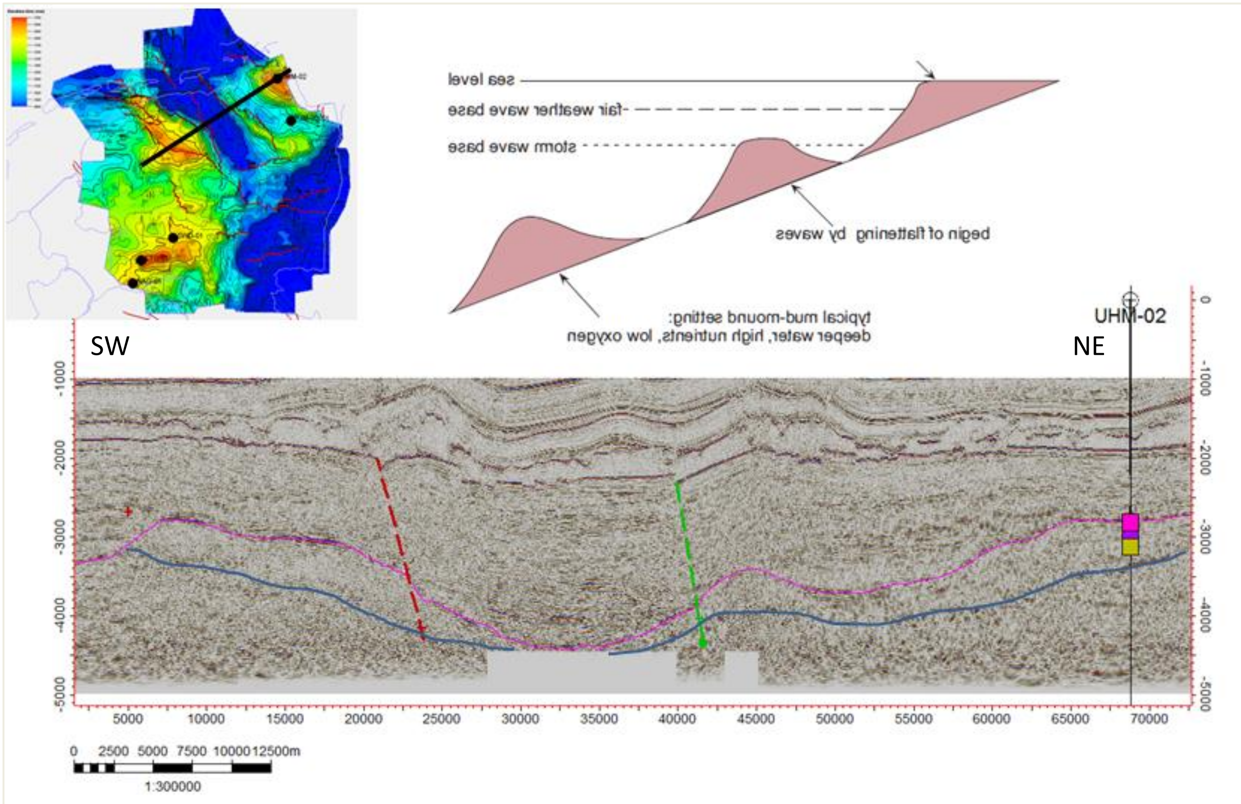


Fig. 8: Seismic section through Uithuizermeeden, Muntendam and Fryslân. Green and red lines are 2 of the mapped faults. Pink is the Top Dinantian as interpreted in TWT (ms). Blue is Top Devonian as interpreted. Small square is outline of the research area and emplacement of the seismic section.

3. Dipping plane theory: The strong reflector found underneath the Dinantian carbonate build-ups, classified earlier as top Devonian (not confirmed by well data) can be traced from Uithuizermeeden to Muntendam and the Fryslân platform. See figure 8 for a reconstruction of this interpretation. Clearly the strong reflector is hard to interpret. The reflector is deep and the seismic acquisition and processing were focused on gas bearing Rotliegend and shallower levels. Interpretation is hindered by lack of well control and this interpretation is just as plausible as the previous one. Schlager (2005) and prof. J. J. G. Reijmer state that Muntendam can be a mud-mound build-up never flattened by wave action (see figure 8) due to a dipping plane (paleotopography) of the Devonian. Question remains: Is the Devonian in this area dipping by tilted fault blocks or due to carbonate build-ups. Kombrink (2010) states that the strong reflector cannot be followed to the Fryslân platform and therefore he proposes the fault block model for explaining the paleotopography. Van Hulten (2012) states that it is very likely that the seismic data underneath Uithuizermeeden reflect a Devonian carbonate build-up. Further research will have to be done to determine the origin of the paleotopography.

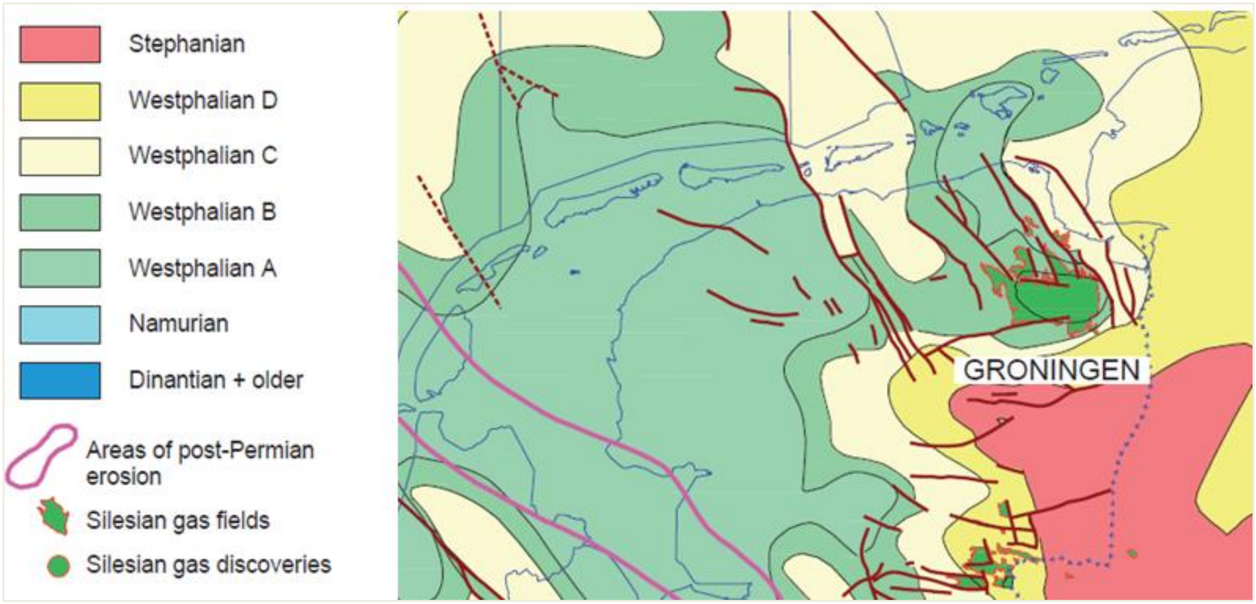


Fig. 9: Sub-crop map of the Westphalian against the Base Permian Unconformity, also showing gas accumulations in Silesian reservoirs. Where the Permian has been eroded, or not deposited, the configuration of top Carboniferous under younger unconformities is shown. (Van Buggenum and Den Hartog Jager, 2007).

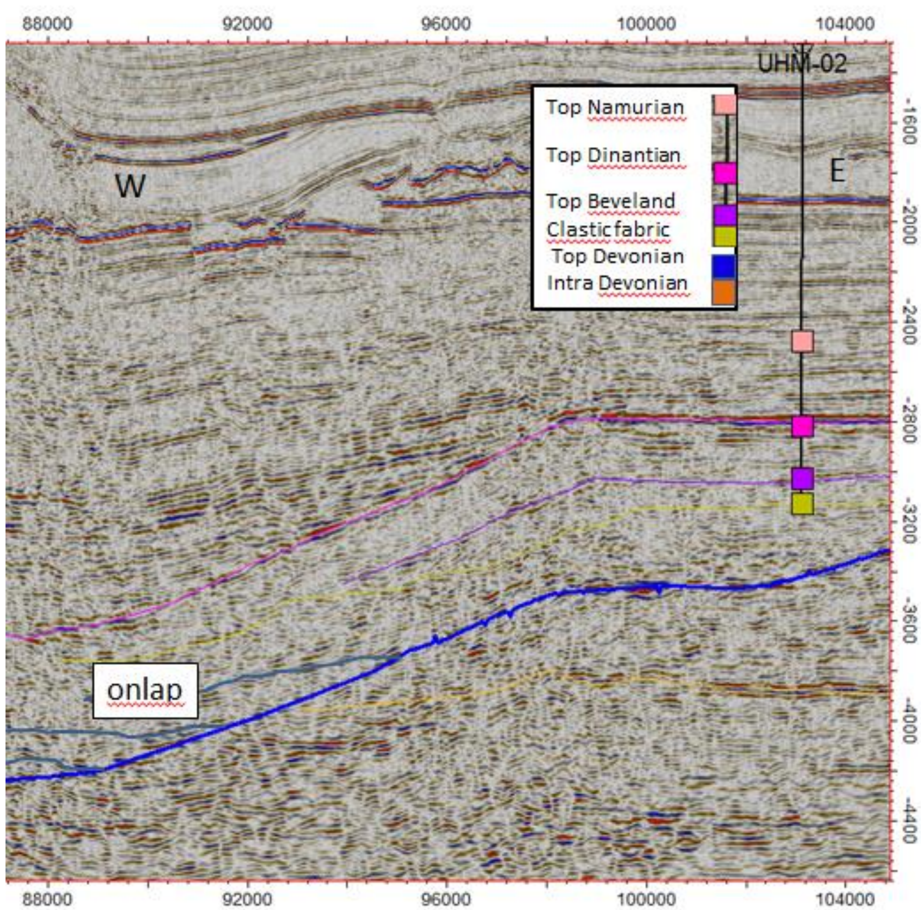


Fig. 10: Detail interpretation of the Uithuizermeeden flat topped platform. Interpretation includes: Top Beveland member, Clastics found during drilling, assumed Top Devonian with onlap and intra Devonian structures.

It is understood that the West-Southwest side of the research area has been subjected to uplift. That however does not explain the paleotopography of the Devonian at the East/Northeast side of the research area. Devonian carbonate build-ups, mostly referred to as Devonian reefs in literature are found in Belgium. In areas where seismic quality is best (the Uithuizermeeden flat topped platform), the strong reflector classified as Top Devonian has been interpreted in detail, see figure 10. The geometry of this interpretation suggests carbonate build-ups underneath the Top Dinantian (Van Hulten, 2012). Structures are seen within the Devonian deposits, that could relate to carbonate build-up, also onlapping features can be recognized . Geluk et al. (2007) mentions carbonate build-ups in the Devonian in this area, see figure 11. Figure 11 is based on wells in Belgium and in the UK and interpretation in between (hence the question mark). A lot of uncertainties, but still a good theory based on the limited data available.

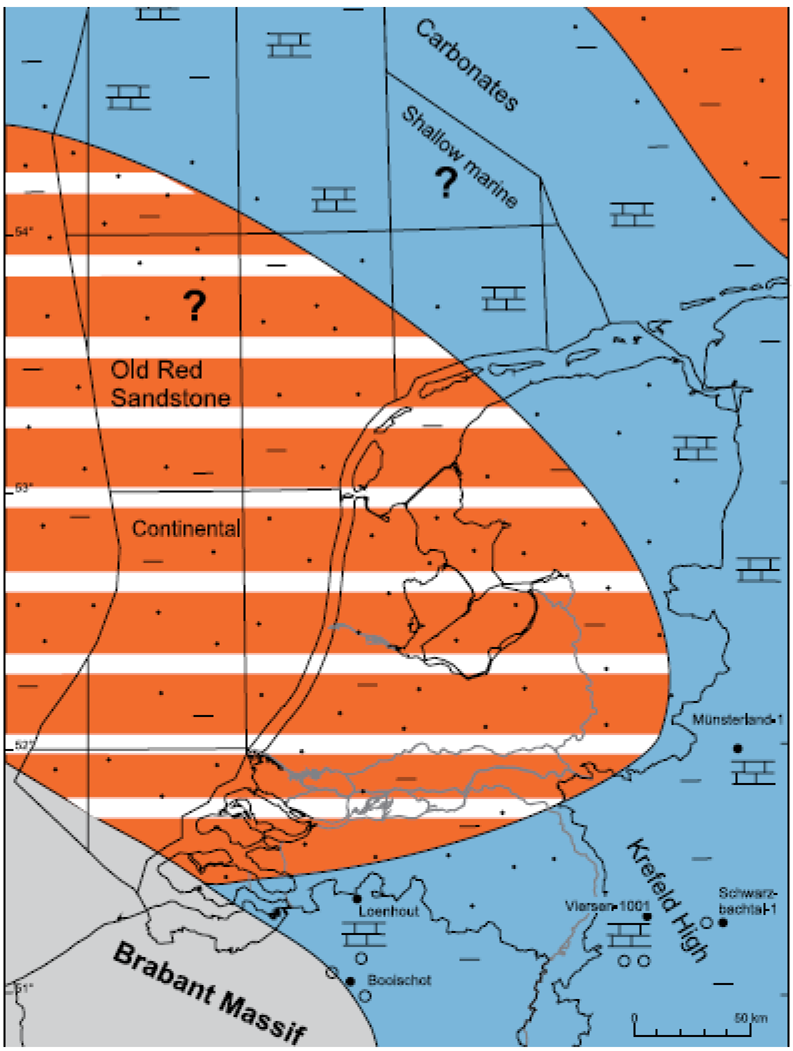


Fig. 11: Paleogeographic sketch map of the late Middle to early Late Devonian (Givetian-Frasnian). The brownish color shows the extent of the continental Old Red Sandstone; in the hatched area it is assumed to be thin or even absent. Blue outlines the presumed occurrence of Middle Devonian carbonates. (Geluk et al., 2007).

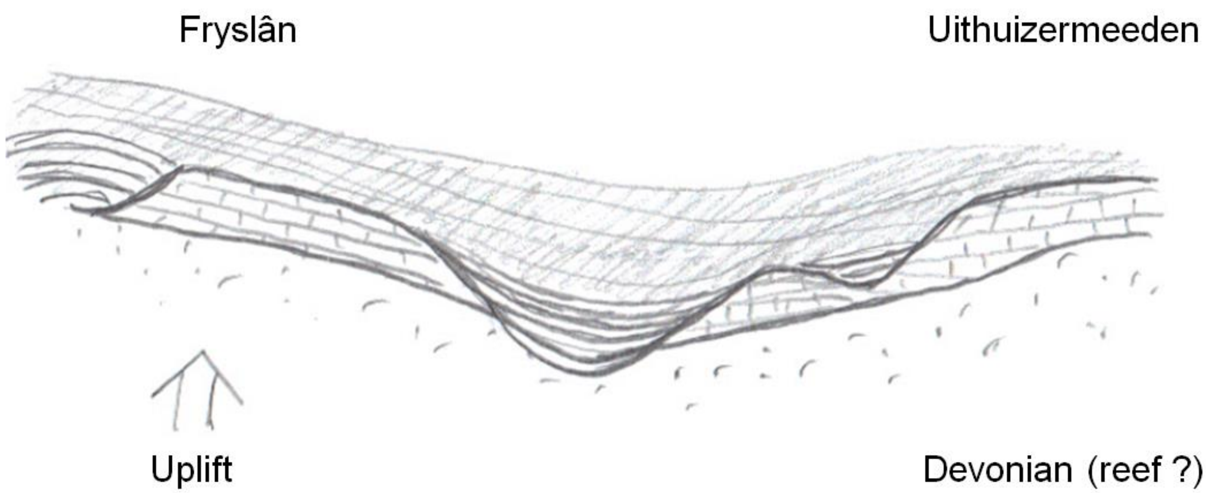


Fig. 12: Schematic overview of The geological history of the Dinantian in the study area (Northern onshore Netherlands), after presenting several theories. Uplift in the Southwest and a Devonian reef in the Northeast.

Conclusions

The South-Southwest area has been uplifted resulting in the tilting of the Fryslân flat topped platform. The North-Northeast Dinantian carbonate build-ups were probably growing on a Devonian reef. The Hantum fault zone has been active since at least Dinantian times creating a deep basin filled with marine shale deposits of Dinantian and Namurian age. The geothermal gradient is estimated to be 37,7°C/km allowing for ductile deformation and maybe even maturation of the potential source rock. Deep marine shales are often organic rich material and can provide source rock for the adjacent carbonate build-ups.

Analogues for Dinantian carbonate build-ups, Northern onshore Netherlands

Introduction

In order to gain more understanding of the Dinantian carbonates onshore Northern Netherlands, analogues need to be studied. In this chapter, the outcropping and tilted platform in Sierra del Cuera (Cantabrian Mountains), the Tengiz oil producing Dinantian platform (Kazakhstan), the seismic response of Dinantian build-ups in the UK and outcrops in Belgium are discussed. Information from Schroot et al. (2006) contributes to this literature study and studies on time-and facies equivalent examples attributes to the understanding of the Dinantian build-ups found in the Northern onshore of the Netherlands in this research report. See figures 1 and 2 for position of these analogues, both todays location and the paleo-location are given for better comparison.

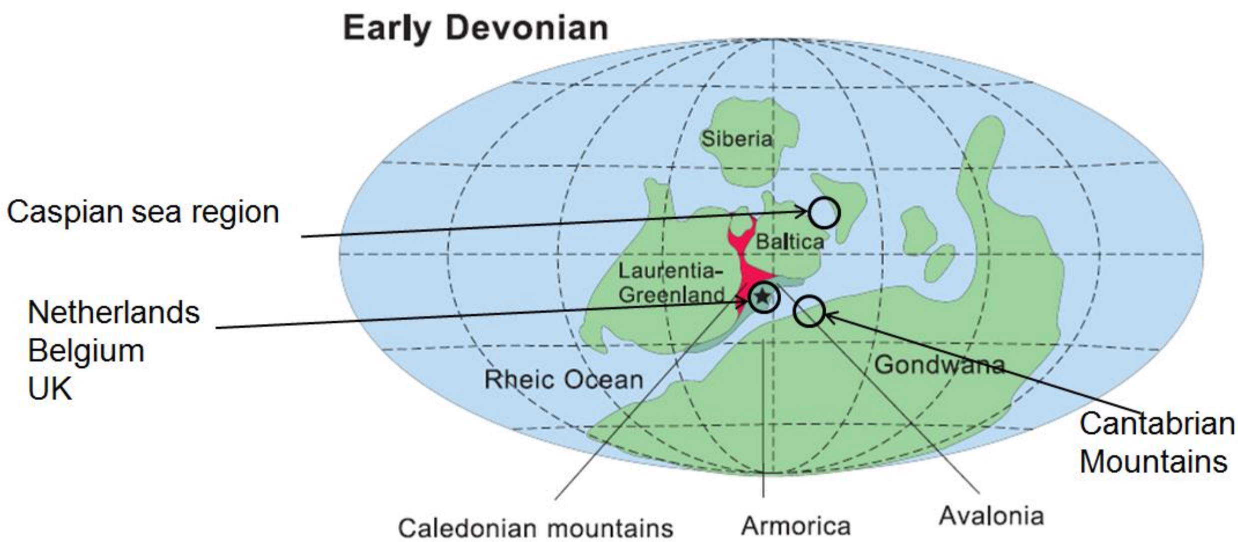


Fig. 1: Plate reconstruction of Avalonia and its collision with Baltica and Laurentia. The star indicates the paleo-position of the Netherlands, Belgium and UK. The paleo-position of Tengiz analogue in the Caspian sea and the Sierra del Cuera in the Cantabrian Mountains are indicated with a circle. After (Geluk et al., 2007). During the Carboniferous, the Netherlands move towards the North ending up at the equator in Dinantian times.

The Uithuizermeeden build-up (flat topped platform) is the best visible structure mapped out in this research. This platform has been studied before and presents the most detail in the seismic available for this study. Therefore comparison with the analogues is done by using Uithuizermeeden as an example for the carbonate build-ups of the northern Netherlands onshore Also notice the rim on Uithuizermeeden, this rim is visible in both the time as well as the depth domain, see figure 6. The rim has also been mapped by Kombrink (2008) who relates it to: (1) platform-margin aggradational growth or (2) differential compaction of the inner platform strata compared to less-compacted marine-cemented boundstone facies at the rim.

Uithuizermeeden	**Carbonate build-up: Visean age**
Build-up depth	4670 m
Build-up thickness	~1500m
Dimension	21 km * 20 km
Slope inclination	+/- 15°

Table 1: carbonate build-up characteristics of Uithuizermeeden.

Fig. 2: Todays location of the analogues; Netherlands, Belgium, UK, Tengiz and the Sierra del Cuera in the Cantabrian Mountains; indicated with a circle.

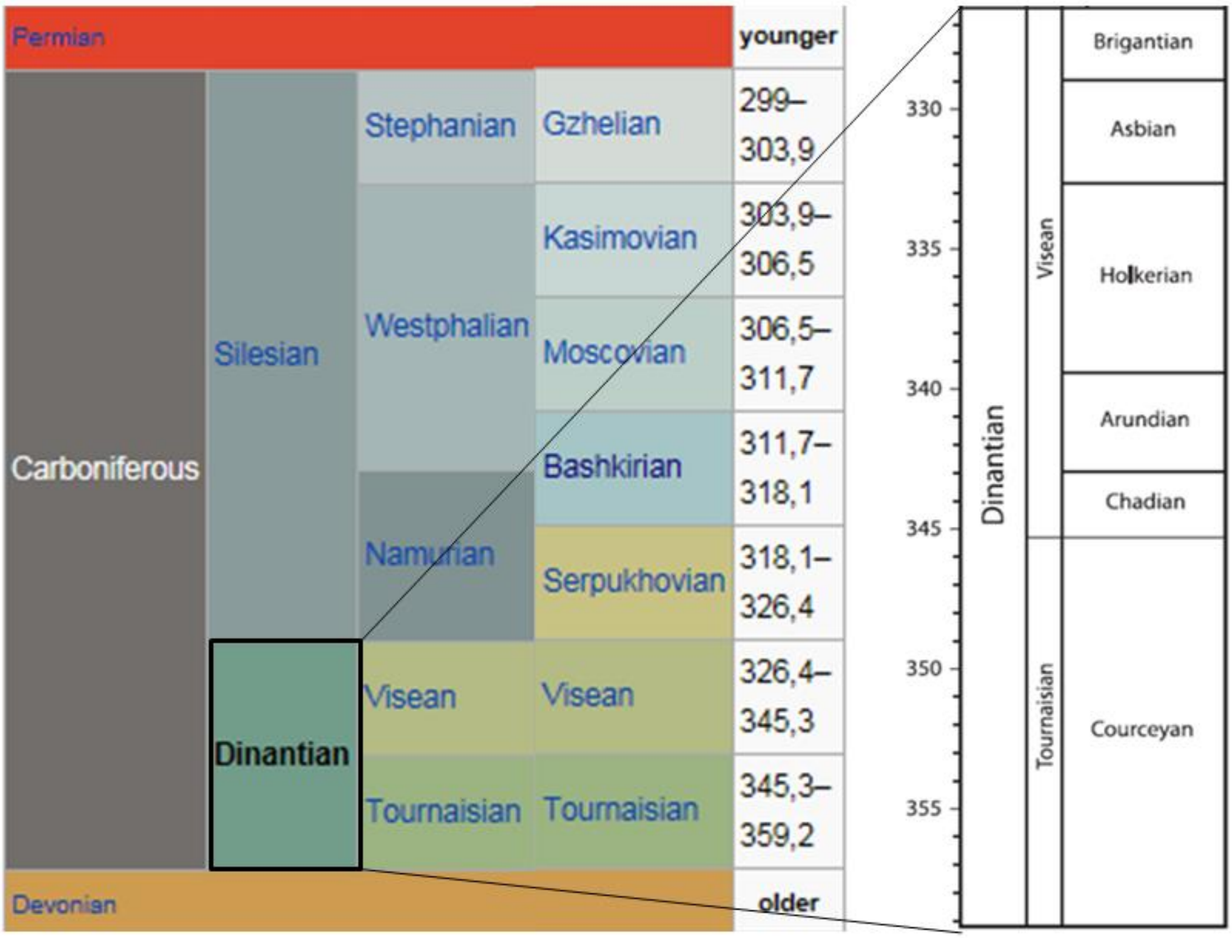


Fig. 3: Time scale and stratigraphy of the Dinantian, after Kombrink (2008).

Tengiz, Kazakhstan

Reservoir Age	Carboniferous Upper Visean, Serpukhovian and Bashkirian
Reservoir average depth	~ 4300 m
Reservoir average thickness	~380 m
Dimension	18 km * 18 km
Slope inclination	+/- 19°

Table 2: Tengiz reservoir characteristics (Ronchi et al., 2009).

The Tengiz field in western Kazakhstan produces oil from an isolated carbonate platform (see figure 4) of Devonian and Carboniferous age. An initial broad Late Devonian platform exhibits accentuated vertical growth with punctuated backsteps during the Lower Carboniferous (Tournaisian and Visean). The uppermost Lower Carboniferous (Serpukhovian) is characterized by several kilometers of platform progradation, seaward of the Late Visean platform break. See figure 5 for these features and figure 6 for the comparison with Uithuizermeeden. Late Visean and Serpukhovian (see figure 3 for timing) boundstone dominates slope lithofacies. The highest rate wells (10,000 to 30,000+ barrels/day) are located at the platform margin and within the slope. Platform and slope production characteristics differ significantly at Tengiz. (Francis et al., 2008). The Tengiz build-up is covered with approximately 150 wells, of which 50 are positioned on the slope.

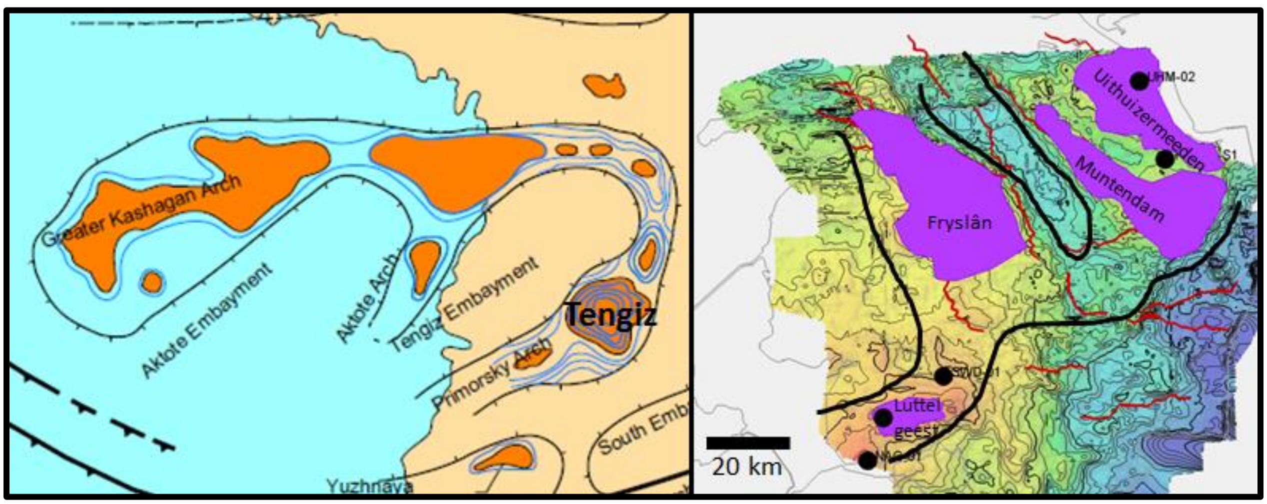


Fig 4: Location and paleotopography of carbonate platform Tengiz (left side), after Francis et al. (2008). Location and paleotopography of Dinantian carbonate build-ups studied in this research (right). Pictures have the same scale.

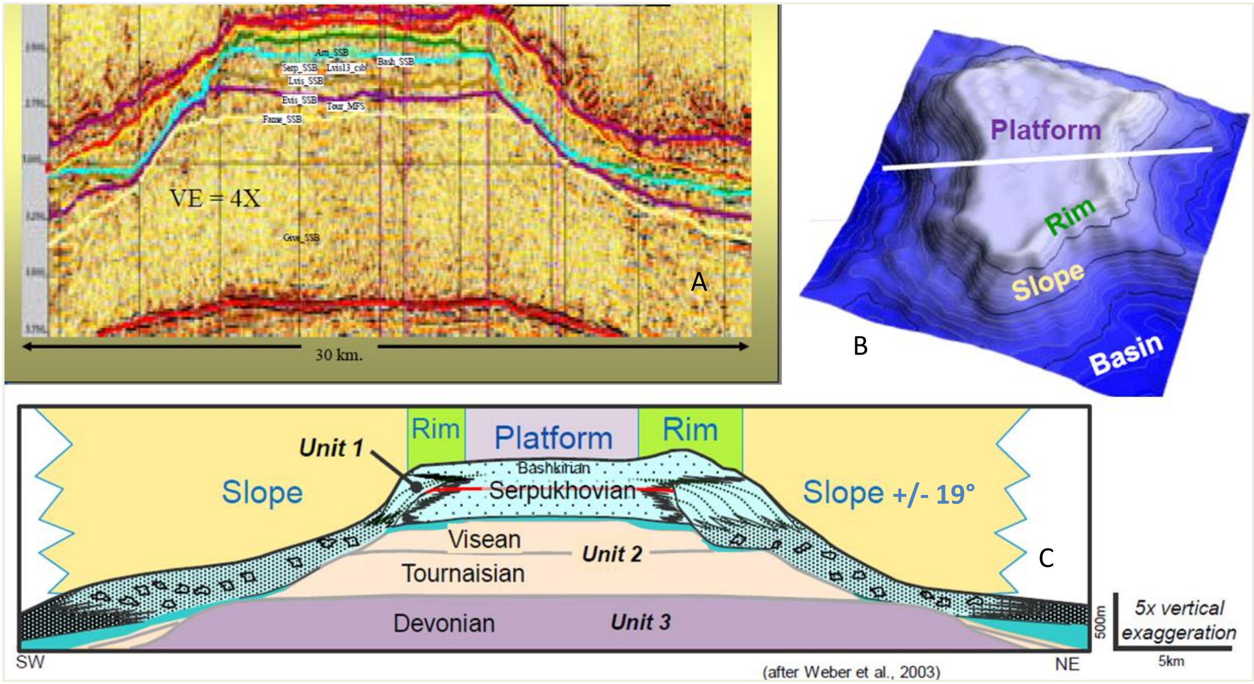


Fig. 5: Seismic section through Tengiz (A). Position marked on the 3D model displayed in depth (B), underneath the depositional model(C), (both have a vertical exaggeration of 5). Depositional model shows backstepping in the Tournaisian and the Visean, progradation in Serpukhovian. After: Narr and Flodin, (2012) and after: Francis et al., (2008).

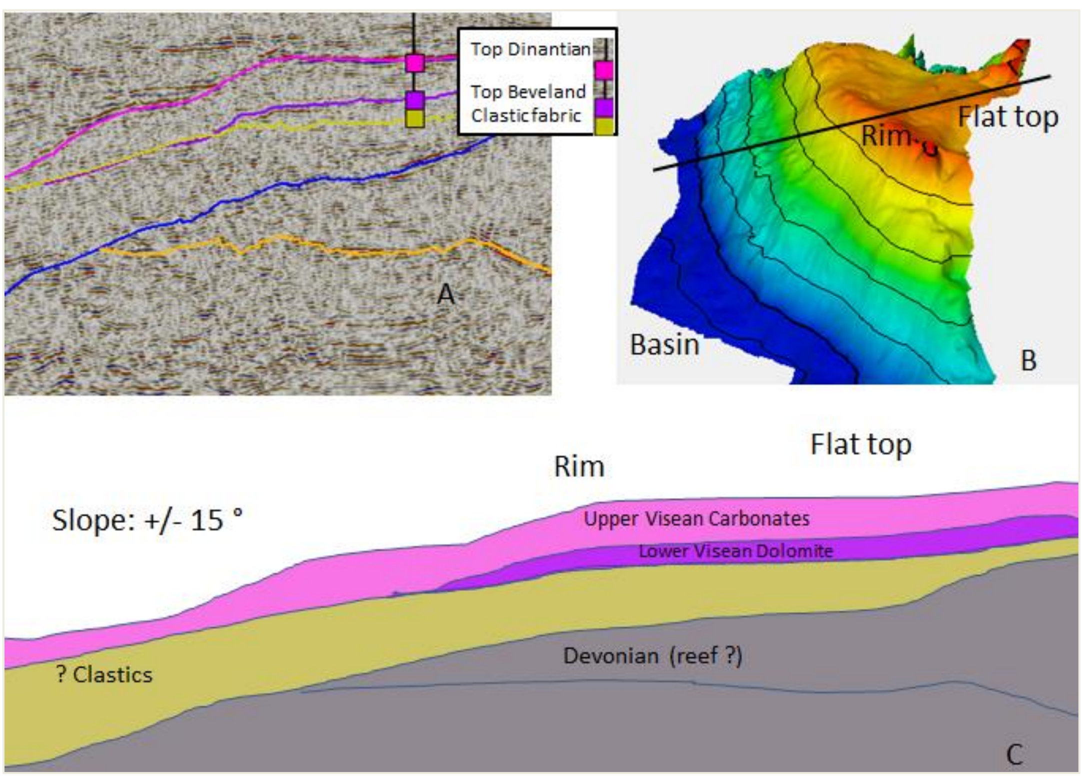


Fig 6: Seismic section through Uithuizermeeden(A), position marked on the 3D model displayed in depth (B) (vertical exaggeration 5). Underneath the depositional model, no vertical exaggeration (C).

The platform edges are abrupt, showing a relatively rapid change from the platform top to the slope environment. Platform deposition includes cycles shoaling upward from open marine packstones to shoal grainstones. A rim (microbial boundstone with scattered mega fossils) is localized to a very narrow belt along the platform margin. Boundstones give way downslope to breccia's and finally argillaceous lime mudstone beds. A variety of porosity types are present; karst zones are best developed in the rim, and dissolution along fractures characterize both the rim and slopes (Harris, 2008). Shallow-burial fractures, formed in carbonate strata prior to significant burial, are most important for reservoir productivity at the Tengiz field. These fractures dip steeply and strike dominantly parallel and/or normal to the local orientation of the depositional margin. They are most well developed in brittle, boundstone-dominant facies of the outer-platform to upper slope environment, see figure 7. See figure 8 for comparison with Uithuizermeeden. Dissolution by fluids (hydrothermal karstification) led to enlargement of the fractures, and therefore these fractures pose both high lost-circulation risk, as well as the reward of highly productive wells by increasing permeability. (Narr and Flodin, 2012). These fractures have been identified by the slope wells by use of FMI logging tools (formation micro imager; in this case fracture analysis).

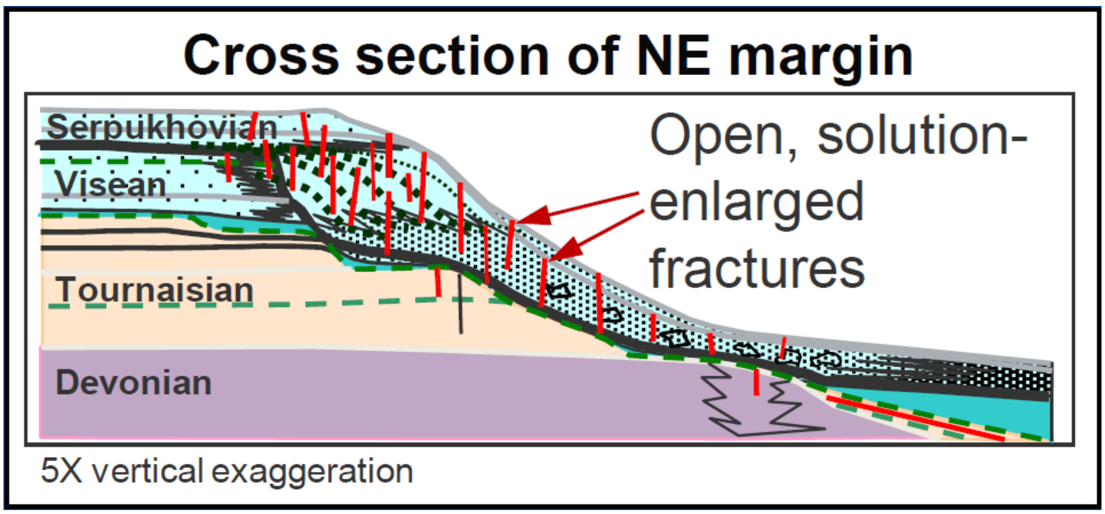


Fig. 7: placement of fractures. (Harris, 2008)

The progradational sequence is very important for the reservoir quality of Tengiz. Slope deposits are deposited in a higher energetic environment, which gives coarser and bigger grains with more initial porosity. Also slopes become unstable and collapse, again increasing initial porosity. The fractures are responsible for secondary porosity and fractures also increase permeability, which is the reason why the highest rate wells are located at the platform margin and within the slope

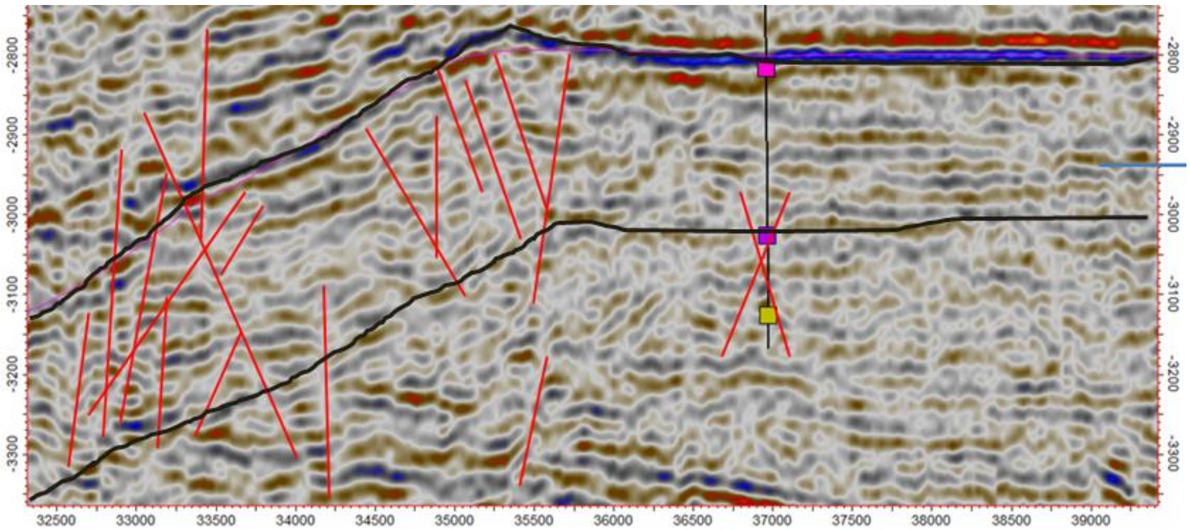


Fig. 8: Enhancement of seismic section through Uithuizermeeden (W-E) and well UHM-02. With discontinuities in the seismic, which might indicate faults with associated fractures, most abundant at the slope and rim.

Conclusion

Tengiz is a Devonian-Carboniferous isolated carbonate platform with steep flanks (19 degrees), the platform comprises of backstepping build-ups in Tournaisian and Visean. In Bashkirian/Serpukhovian the platform progradates with significant slope deposits. The reservoir quality at the slope of the platform is dependent on fractures and diagenesis. Uithuizermeeden has the same dimensions as Tengiz, same geometry and a comparable burial depth (see table 1 and 2).

Highstands and lowstands, which control progradating sequeces, cannot be compared, for Tengiz paleo-position during the Dinantian was more to the North and on the east side of Baltica. In this period Tengiz and Uithuizermeeden were connected through open water, therefore sea-level must have been the same. However, Tengiz was in a different tectonic regime and the relative sea-level might have been different from the Netherlands. The high and lowstands of Uithuizermeeden should therefore be compared with Belgium and UK analogues. Also the carbonate factory of Tengiz might have been different, due to different latitudes in Dinantian. Nevertheless figure 6 shows that the slope of Uithuizermeeden consists of a progradational sequence. These slope deposits might form a better reservoir than the platform flat, for the initial porosity is bigger in these higher energy environment deposits. Porosity on the flat is low as shown by well UHM-02 , which encountered compacted mudstone with cemented fractures. Professor J. J. G. Reijmer states that Dinantian microbes are able to build steep slopes, which can become unstable resulting in fractures. Fractures can be expected in the slope deposits, see figure 8. The presence of open fractures increases reservoir quality (permeability) and at the same time poses a threat for sealing capacity.

Belgian outcrops

The Dinantian outcrops in Belgium and near Aachen, just across the border in western Germany, are exposed in many quarries and (rail) road cuts, see figure 9 for the location of these outcrops. The outcrops have been intensively studied. Unfortunately, the southern Belgium area has been affected by the Variscan Orogeny, which sometimes obscures the comparison. During the Dinantian, the overall depositional setting of the area south of the London-Brabant Massif can be characterized as a platform slope. In the Tournaisian, the succession starts on a ramp. In the Visean the succession develops into a southward progradating platform. Despite marked differences in the various sedimentological cycles, the overall setting remains in agreement with deposition on the lee side of the London-Brabant Massif. (Van Hulten and Poty, 2008).

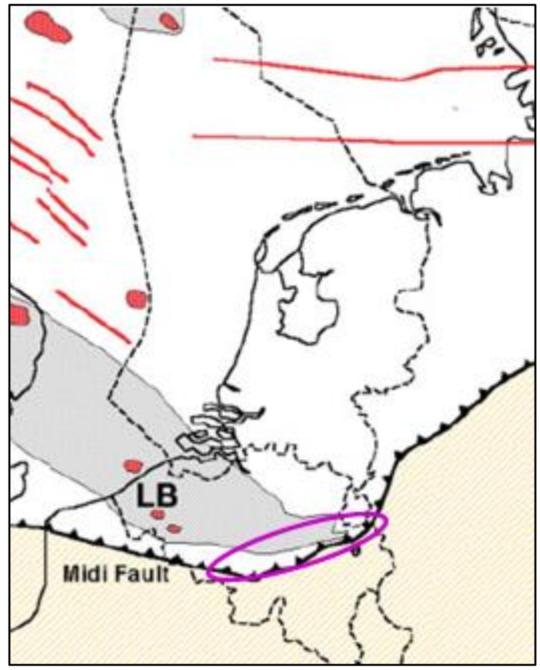


Fig. 9: Dinantian outcrops that have been studied in purple circle. Variscan orogeny and LB is London Brabant massif. The Midi fault is part of the Variscan suture. After Van Hulten (2012)

Fig. 10: Dinantian carbonate mudstone with karst infill from Namurian, at Argenteau, Belgium. Picture taken by Bastiaan Jaarsma.

Fig. 11: Dinantian outcrop in a quarry near Stolberg, Germany. Tournaisian carbonate mudstones with karst holes. Picture taken by Bastiaan Jaarsma).

A restricted fauna characterizes the Waulsortian carbonate build-ups, named after the small town of Waulsort in the southern part of Belgium (Lees and Miller 1995). Their development, in a more ramp-type depositional setting and relatively deep water, makes them incomparable to high energy build-ups, expected north of the Brabant Massif. The lenticular Waulsortian mounds are unlikely candidates for a good reservoir (Van Hulten and Poty 2008). They cannot develop the grainstone layers, as described from Tengiz (Weber et al. 2003), that make those platforms so attractive as a reservoir .

In the Belgian Campine Basin a number of these Late Dinantian build-ups have been extensively studied for gas storage purposes. The Heibaart and Poederlee build-ups are regarded as microbial build-ups, essentially consisting of pelletoidal, micritic limestone with little or no initial porosity. Reservoir properties were greatly enhanced by early karstification (see figures 10 and 11 for analogue in outcrop) at the end of the Dinantian, formation of fracture networks, and paleokarst reactivation. This resulted in the Heibaart case in average porosities of 2-3 % and permeability's up to 3 Darcy. It has been suggested that the Heibaart and Poederlee build-ups formed on fault bounded, periodically uplifted domal structures, which resulted in a higher elevation in the first place, but also favored the initial karstification (Van Hulten and Poty, 2008. And references therein).

The Belgium area provides a good model for the understanding of the dolomite diagenesis of the Dinantian-aged carbonates. Dolomitization is one of the more important factors that can provide a good reservoir in carbonate rock. In southern Belgium a major low stand is documented during lower Upper Tournaisian and Lower Visean, giving rise to dolomitization of the coarse grained limestones of the high-stands in the underlying sequences. Dolomitization is limited to carbonates stratigraphically positioned below a low stand in the Late Visean (Van Hulten and Poty, 2008), allowing meteoric water to migrate into the subsurface. From this information it can be concluded that widespread dolomitization can be expected over large areas in the shallower early Dinantian rocks, as a consequence of some of these major low stands. Such dolomites are well developed in the Lower Carboniferous-aged carbonates, but also in the Mississippi area, in the West Canadian Basin, in southern China and in the English Midlands. For Canadian Dinantian petroleum reservoirs, dolomitization is an important factor providing reservoir quality (Van Hulten and Poty, 2008).

Conclusion
The Dinantian carbonate outcrops in Belgium and Germany are a good analogue for the carbonates build-ups just North of the London Brabant massif. But when compared to the study area, the carbonate build-ups are quite different due to paleotopography of the London Brabant massif. Sea-level changes and the dolomitization process on the other hand can be compared. The Beveland member can be correlated to the widespread dolomitization as described by Van Hulten and Poty (2008), the member consists of dolomites of Lower Visean age. Possibly formed during the lowstand as recorded in Southern Belgium, followed by a progradating sequence in the Upper Visean (see figure 6).

Sierra del Cuera, Cantabrian Mountains, Spain

Sierra del Cuera, Cantabrian Mountains, Spain	Carbonate build-up: Bashkirian and Moscovian
Build-up depth	Outcropping tilted platform
Build-up thickness	1000m
Dimension	10 km * ? km
Slope inclination	+/- 25°

Table 3: Carbonate build-up characteristics of Sierra del Cuera.

Verwer (2008) describes this platform in his dissertation: "Spatial models of carbonate platform anatomy". Because the platform is tilted and outcropping each facies can be described by a depositional setting.

The inner platform deposits contain shoaling-upward cycles with a transgressive interval of coated grainstones with oncoids, followed by normal marine algal-skeletal packstone-wackestone that form massive banks, and bioclastic grainstones to packstone, and, near top, restricted lagoonal peloidal packstone to grainstone with calcispheres. These cycles have a thickness between 2,5-25 m and can be traced from the platform break into the platform interior for a distance of at least 6 km. From the platform interior towards the platform break there is a one-kilometer-wide zone that represents a lateral facies change from inner to outer platform. The mud-rich banks of the inner platform grade laterally into massive units of boundstone facies that alternate with thick crinoid packstone intervals and thin beds of ooid-coated skeletal grainstones. Generally, in the progradational setting, ooid grainstone shoals dominate, whereas during aggradation, boundstone prevails in the outer platform. The upper slope can be divided into two distinctly different microbial boundstone margins: (1) low-angle slopes and ramps, deposited during the nucleation phase of the platform, of nearly pure micritic limestone, and (2) steep (25° to 45°) slopes where microbial boundstone dominates the uppermost 300m. The boundstone alternate thin bedded crinoid-bryozoan grainstone and skeletal wackestone with red-stained micritic matrix. The boundstone facies appears to form massive, several-meter-thick units that do not exhibit a mound-shape or depositional relief on the sea floor. The lower slope deposited below a

300m paleo-water depth, consists of clast supported breccia. Clasts are mostly derived from the upper-slope microbial boundstone zone. The toe-of-slope deposited below 600m paleo-water depth, consists of argillaceous lime mudstone beds interfingered with grainstone to wackestone intervals of mostly platform top derived skeletal and peloidal grains and thick intervals of upper-slope-derived breccia. See figure 12 for a digital outcrop model as derived from field observations and measurements.

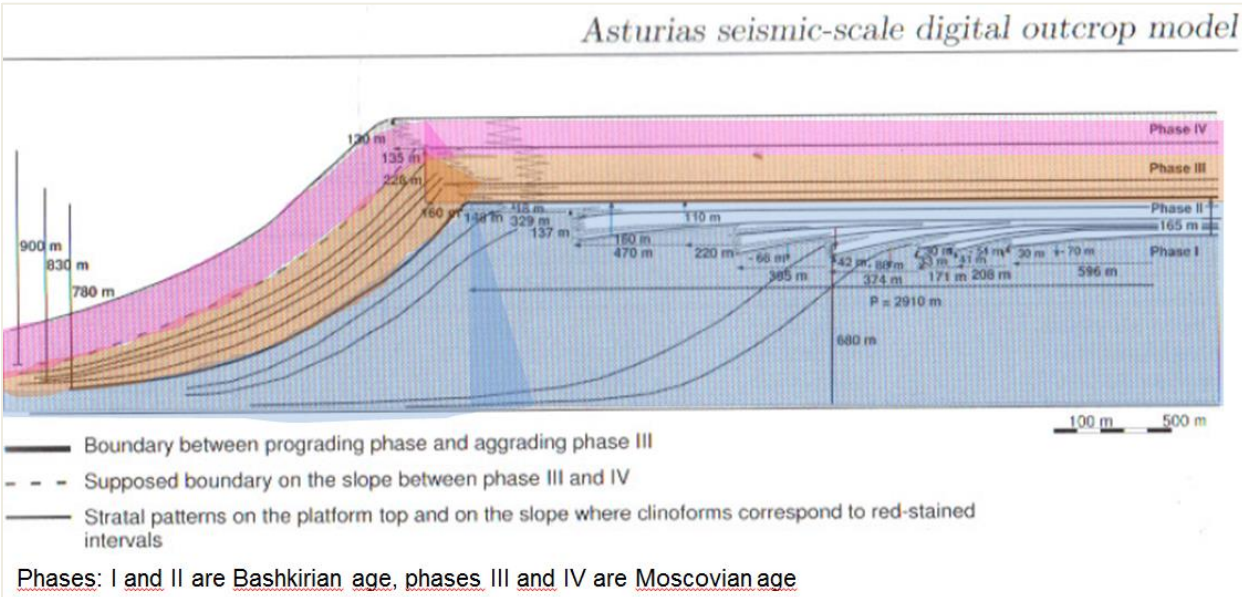


Fig. 12: Digital outcrop model; blue = progradational sequence in Bashkirian, orange = aggradational sequence in Moscovian, pink = progradational sequence in Moscovian. After Verwer (2008)

Timing of the highstands and lowstands cannot be compared, for the paleo-position of Sierra del Cuera during the Dinantian was more to the South and on the Gondwana continent on the other side of the Rheic Ocean. In this period Sierra del Cuera, Tengiz and Uithuizermeeden were connected through open water, therefore sea-level must have been the same. However, Sierra del Cuera was in a different tectonic regime and the relative sea-level might have been different from the Netherlands. The high and lowstands of Uithuizermeeden should therefore be compared with Belgium and UK analogues. Nevertheless slope deposits in Uithuizermeeden as demonstrated by the analogue Sierra del Cuera might have better reservoir quality, for the initial porosity is bigger in these higher energy environment deposits.

The relative percentages per area of slope lithofacies during the late Bashkirian have been calculated, results are in table 3. Boundstones dominate the upper slope between depths of 0-300 m. The lower slope is more breccia dominated, depths of 300-850m).

Relative percentage of lithofacies area	Late Bashkirian progradation	Latest Bashkirian to Vereian aggradation
Whole slope		
Boundstone	40%	33%
Breccia	50%	52%
Redeposited and 'red-stained' layers	10%	15%
Uppermost slope (0-150 m)		
Boundstone	99.5%	87%
Breccia	0.4%	1%
Redeposited and 'red-stained' layers	0.1%	12%
Lower part upper slope (150-300 m)		
Boundstone	83%	34%
Breccia	13%	50%
Redeposited and 'red-stained' layers	4%	16%
Lower slope (300-500 m)		
Boundstone	10%	-
Breccia	80%	92%
Redeposited and 'red-stained' layers	10%	8%
Lower slope to toe-of-slope (500 to 700-850 m)		
Boundstone	-	-
Breccia	79%	72%
Redeposited and 'red-stained' layers	21%	28%

Table 4: Lithofacies percentages in the slope of Sierra del Cuera, from Verwer (2008).

Verwer (2008) compares the Sierra del Cuera and Tengiz as follows: both have a highly productive microbial cement boundstone factory extending from the platform break to nearly 300 m depth and a lower slope dominated by breccia's and grain flow deposits derived from the margin and slope itself.

Conclusion:
As seen in the core taken from UHM-02, boundstone is a poor reservoir. As seen in Tengiz and Sierra del Cuera, slope deposits from progradating sequences, containing breccia, on the other hand seem to have higher initial porosity. This has the potential of providing a much better reservoir than the inner platform strata.

UK seismic response

UK seismic response **UK**	**Carbonate build-up: Visean age**
Build-up depth	500m - 1000m
Build-up thickness	~800m
Dimension	~12 km * ~12 km
Slope inclination	+/- 15°

Table 5: UK Dinantian build-up characteristics (Evans and Kirby, 1999).

Luttelgeest	**Carbonate build up: Visean (Chadian, Arundian Holkerian)**
Build-up depth	4300m
Build-up thickness	550m
Dimension	7,5 km* 20 km
Slope inclination	+/- 10°

Table 6: carbonate build-up characteristics of Luttelgeest.

The establishment of carbonate platforms on structural highs in the UK only took place during late Dinantian times after a period of progressive flooding. Rimmed shelf platform are mainly limited to the Late Visean. During tectonic activity the size of carbonate ramps or shelves generally decreased due to inundation of the hanging walls and emergence of the footwalls. Intervals of tectonic quiescence are characterized by downward progradation of rimmed shelves over hanging wall slopes. Overall, the Dinantian carbonate sequence varies from 500 to 1000 m in thickness on the structurally elevated areas. The most important reason for carbonate production to stop in northern England has been increased siliciclastic input during the Brigantian and earliest Namurian. Since the main sediment source was located in the north, the northerly located platforms experienced mixed carbonate-siliciclastic sedimentation during the Early Brigantian. In the south, where the siliciclastic sediment supply remained very limited until far into the Namurian, carbonate production must have ceased for another reason (changing circulation or temperature). (Kombrink, 2008. And references therein)

Although the number of boreholes in the region is limited and much of the interpretations is based on cuttings. Evans and Kirby (1999) managed to describe the seismic response of different facies within Dinantian (Visean age) carbonate build-ups:
“Seismic reflection data reveal two distinct seismic facies associated with the Dinantian succession.

1. A 'stripy' facies with reflectors of moderate to high amplitude, which are subparallel and sub-horizontal and of moderate lateral continuity (see figure 13). Ties to the Whitmoor well in the Craven Basin to the north of the Pendle Fault and to outcrop in the Skipton Anticline, indicate that this stripy facies arises from alternating basinal (deeper-water) limestones and mudstones of the Worston Shale Group.
2. A 'quieter' facies with discontinuous low-amplitude reflectors. Its base commonly lies above a series of high-amplitude reflections and its top is marked by a high-amplitude reflection. The succession encountered in the Roddlesworth well demonstrates that this seismic facies corresponds to a thick sequence of shallow-water platform carbonates overlying a thin and unbottomed series of clastic sediments.”

(Evans and Kirby, 1999. And references therein)

The seismic section from figure 13 shows a lot of similarities with the Luttelgeest build-up for comparison see figure 14. Geometry and Dimension match much better than the Uithuizermeeden build-up. The Central Lancashire High comprises of Chadian, Arundian, Holkarian, Asbian and Brigantian, whereas Luttelgeest is missing Asbian and Brigantian, which might have been eroded by uplift or never been deposited due to limited growth space. Nonetheless, the ‘stripy’ and ‘quiet’ facies are seen in the seismic data available for this study (see figure 15 for comparison of the seismics).

The seismic response found by Evans and Kirby (1999) cannot be linked 1 on 1 to the seismic response of this research, for extraction and processing of these lines are unknown. Nonetheless, as described in the chapter methods, seismic mapping was done by following a sharp blue reflector defined as Top Dinantian by UHM-02, mapping of onlapping features and following transparent seismic facies.

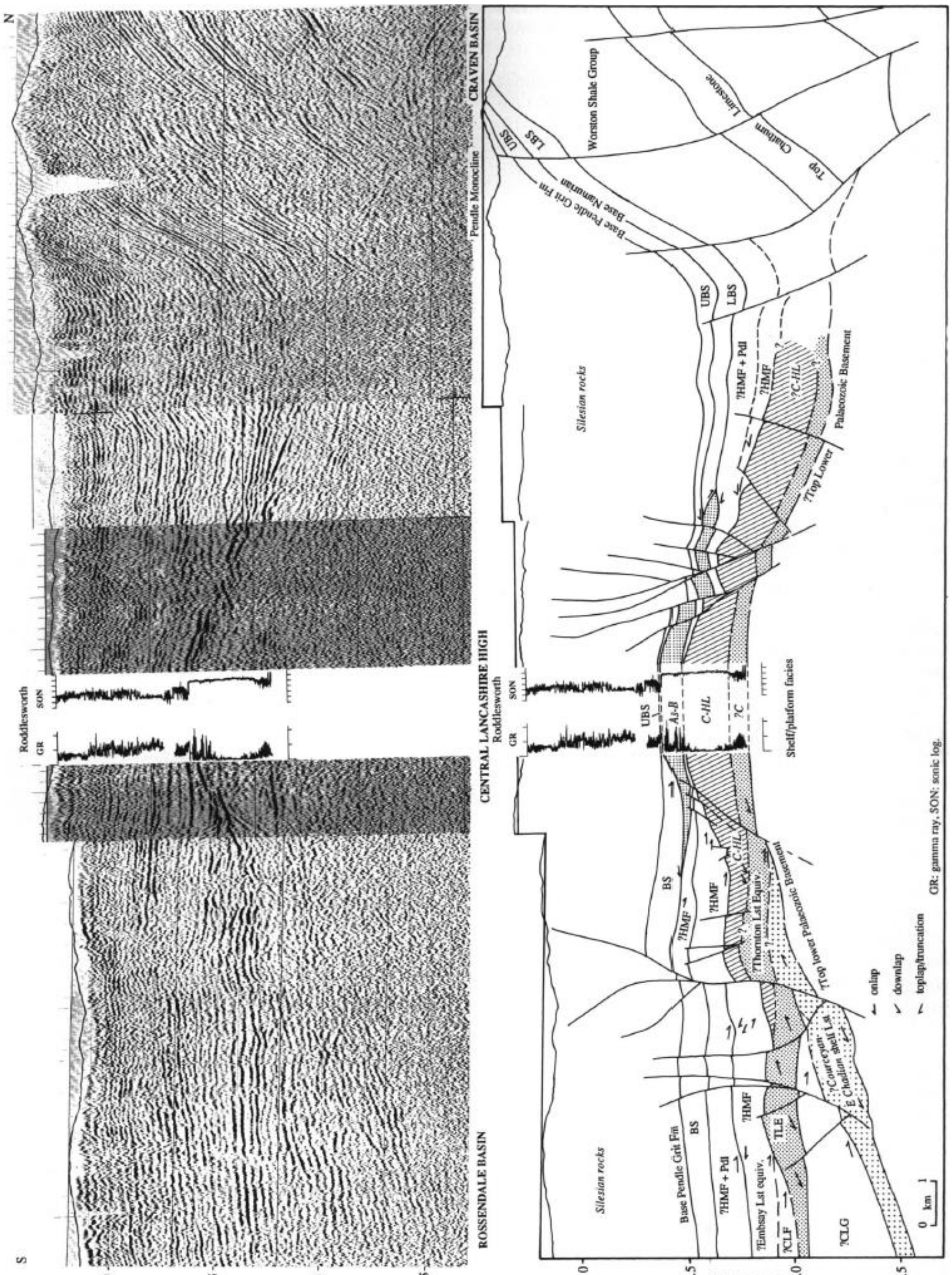


Fig. 13: Seismic reflection profile across the Central Lancashire High, illustrating the main unreflective platform carbonate build-up of Chadian to Arundian/Holkerian age and the more reflective and stripy successions interpreted as basinal-facies (seismic courtesy of Amoco (UK) Exploration Company). (Evans and Kirby, 1999).

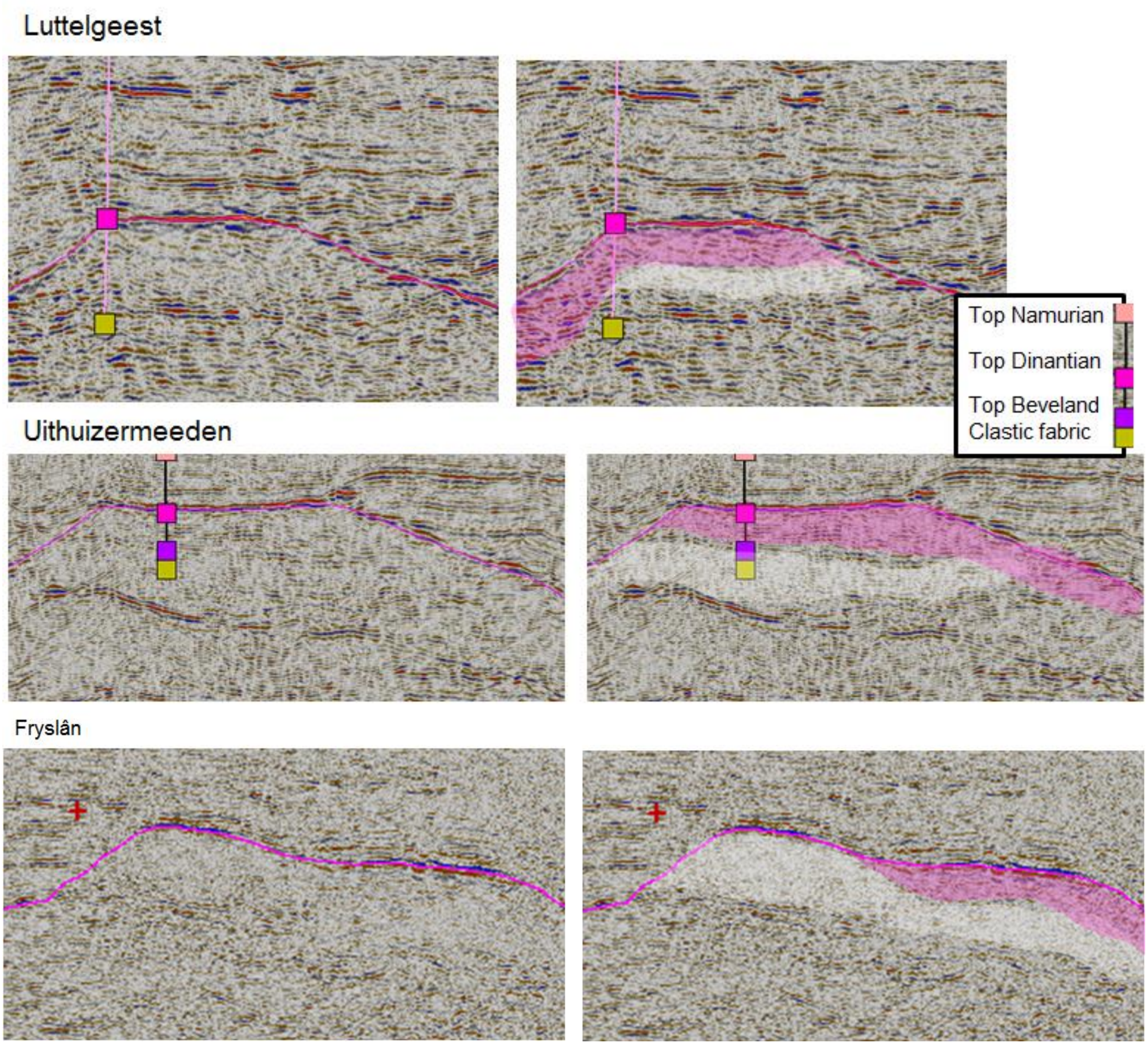


Fig. 14: Seismic character of the Dinantian build-ups studied in this research. Pink color represents 'stripy' seismic facies and the white represents the 'quiet' seismic facies or more transparent character.

Conclusion
The 'stripy' phase found on top of the platforms is related to an alternating basinal limestones and mudstones sequence by Evans and Kirby (1999). LTG-01 and UHM-02 encountered mudstones at Top Dinantian, the basinal deposits could correlate with the supposed drowning of these build-ups. The 'quiet' phase with a strong reflector at the bottom, found underneath the 'stripy' phase, has been related to shallow-water carbonates overlying a thin series of clastic sediments by Evans and Kirby (1999). Shallow water carbonates, with clastics underneath, corresponds to the lithology's found in LTG-01, also UHM-02 has encountered clastics underneath the Beveland member. The Beveland member is dolomitized, Evans and Kirby (1999) do not describe this succession. This correlation on seismic response is debatable, but defendable.

Note: Kombrink (2008) also mapped Uithuizermeeden and a part of the Fryslân build-up. He also compared Sierra del Cuera and Tengiz with Uithuizermeeden. This study provides much more detail, due to access to the well UHM-02, which was confidential at the time Kombrink was studying the area. Kombrink (2008) also compared Evans and Kirby (1999) seismic response of the UK to Uithuizermeeden (only Uithuizermeeden) and found no comparison. As seen in the chapter methods, the Top Dinantian in this study has been mapped on several indicators, one of the being the trgutteridgeansparent/'quiet' phase recognized in the seismics. Though Evans and Kirby (1999) provide information that helps understand the build-ups in the onshore Northern Netherlands.

Conclusion

The Dinantian carbonate build-ups of the onshore Northern Netherlands, can be compared to Dinantian outcrops in Belgium when studying highstands and lowstands during Dinantian times. For karstification features however, the comparison is compromised by differences in tectonic history. Also the geometries cannot be compared for the carbonate build-ups in Belgium developed in a ramp setting due to the paleotopography of the London Brabant Massif where-as the build-ups in the study area are isolated flat topped platforms and mounds. Tengiz and Sierra del Cuera can be compared in geometry and depositional setting. There is a lot of information on (differences in) reservoir quality on Tengiz and both analogues give much information on sequence stratigraphy. When Uithuizermeeden is compared to these 2 analogues, the idea arises that the best reservoir quality for Uithuizermeeden can be expected at the slope of the platform, due to progradation and fracturing. Comparison with Dinantian carbonate build-ups from the UK can provide information on seismic response and can help future interpretation, in detail, of the onshore Northern Netherlands build-ups. Because the seismic quality is best at Uithuizermeeden; this build-up has been mapped in detail. Seismic facies has been determined for 3 build-ups, after Evans and Kirby (1999), and progradating sequences can be recognized at Uithuizermeeden, Luttelgeest and Fryslân. This gives the idea that slope deposits will be different from the interior for all carbonate build-ups found in the Northern onshore Netherlands (as seen in Tengiz and Sierra del Cuera). Future drilling will have to prove this point.

Conclusions

Carbonate production in Dinantian times comprised mostly on microbial mats, which need nutrients such as O, C, N and P. These nutrients are more abundant at greater depths, and they need upwelling in order to reach the water column with enough light for photosynthetic processes. A typical depth related to these processes is: 0-100m. An alkaline environment induces carbonate precipitation from microbial mats by, either warm temperatures, fluvial water influx or by dissolution of CO2. The best place for Dinantian microbial mat build-ups would typically be near a continental shelf at warm to moderate temperatures (latitudes) near an upwelling zone.

Only 2 wells penetrated the Dinantian carbonate succession in the Northern onshore Netherlands: UHM-02 and LTG-01. LTG-01 does not contain late Visean (Asbian and Brigantian) deposits, UHM-02 on the other hand contains stratigraphy of the whole Visean. Both wells in comparison of the Southern onshore region miss the Tournaisian. There is no data supporting the timing of the other carbonate build-ups and whether the Beveland member (dolomite) is present in these areas. The Dinantian buildups encountered were, in general, deposited in a muddy environment with fine grained matrix with a lower initial reservoir quality. Also interbedded shale units found in LTG-01 and UHM-02 may form a baffle to vertical fluid flow. Because of the deep burial depth and diagenetic changes in the carbonates, the reservoir quality will be highly dependent on the secondary porosity developed through time: karstification, dolomitization and fracturing. UHM-02 and LTG-01 show signs of karstification (thin section scale). Dolomitization in these wells did not improve porosity and/or permeability. Karstification along faults and/or fractures during hydrothermal circulation is still a possibility, which is most likely to be found in slope deposits or near big faults. Diagenetic processes are extremely complicated and non-homogeneous. Especially when a large amount of time was available. Earlier karst features might have been cemented again at a later stage and also recrystallization processes might have taken place in multiple stages.

seismic mapping has lead to the identification of 4 build-up structures: Uithuizermeeden, Fryslân, Luttelgeest and Muntendam. Because of significant differences in geometry, the build-ups can be further subdivided. Fryslân is subdivided in Blija deep and Tytsjerk. Whereas Blija deep seems to be isolated from the rest of the Fryslân build-up and bounded by faults. The Muntendam build-up is subdivided in Bedum and Meeden. The Muntendam build-up is buried deeper than the other build-ups. Uithuizermeeden and Fryslân have flat tops, regardless whether this is due to erosion or sea level base, Meeden on the other hand has an undulating top. Blija and Luttelgeest are convex/mound build-ups. There is a strong reflector present underneath each build-up, the strong reflector is classifies as base of Dinantian Carbonates/Top Devonian, as recorded in LTG-01. The Dinantian build-ups were built on a dipping paleotopography, which could indicate either fault movement or Devonian reefs/build-ups. The Luttelgeest build-up is much thinner than the Fryslân and Uithuizermeeden build-up.

The South-Southwest area has been uplifted resulting in the tilting of the Fryslân flat topped platform while faulting isolated the Blija part. The North-Northeast Dinantian carbonate build-ups werepossibly growing on a Devonian reef. The Hantum fault zone and the Lauwerszee Trough separated the carbonate build-ups in the West from the carbonate build-ups in the East. The Hantum fault zone has been active since at least late Carboniferous, creating a deep basin filled with marine shale deposits of Dinantian and Namurian age. The geothermal gradient is estimated to be 37,7°C/km allowing for ductile deformation and (over)maturation of these shale deposits. Deep marine shales are often organic rich material and can provide source rock for the adjacent carbonate build-ups.

The Dinantian carbonate build-ups of the onshore Northern Netherlands, can be compared to Dinantian outcrops in Belgium when studying highstands and lowstands during that period. For karstification features however, the comparison is compromised by differences in tectonic history. Also the geometries cannot be compared for the carbonate build-ups in Belgium developed in a ramp setting due to the paleotopography of the London Brabant Massif whereas the build-ups in the study area are isolated flat topped platforms and mounds. Tengiz and Sierra del Cuera can be compared in geometry and depositional setting. There is a lot of information on (differences in) reservoir quality on Tengiz and both analogues give much information on sequence stratigraphy. When Uithuizermeeden is compared to these 2 analogues, the idea arises that the best reservoir quality can be expected at the slope of the platform, due to progradation and fracturing. Comparison with Dinantian carbonate build-ups from the UK can provide information on seismic response and can help future interpretation, in detail, of the onshore Northern Netherlands build-ups. Because the seismic quality is best at Uithuizermeeden; this build-up has been mapped in detail. Seismic facies has been determined for 3 build-ups, after Evans and Kirby (1999), and progradating sequences can be recognized at Uithuizermeeden, Luttelgeest and Fryslân. This gives the idea that slope deposits will be different from the interior for all carbonate build-ups found in the Northern onshore Netherlands (as seen in Tengiz and Sierra del Cuera). Future drilling will have to prove this point.

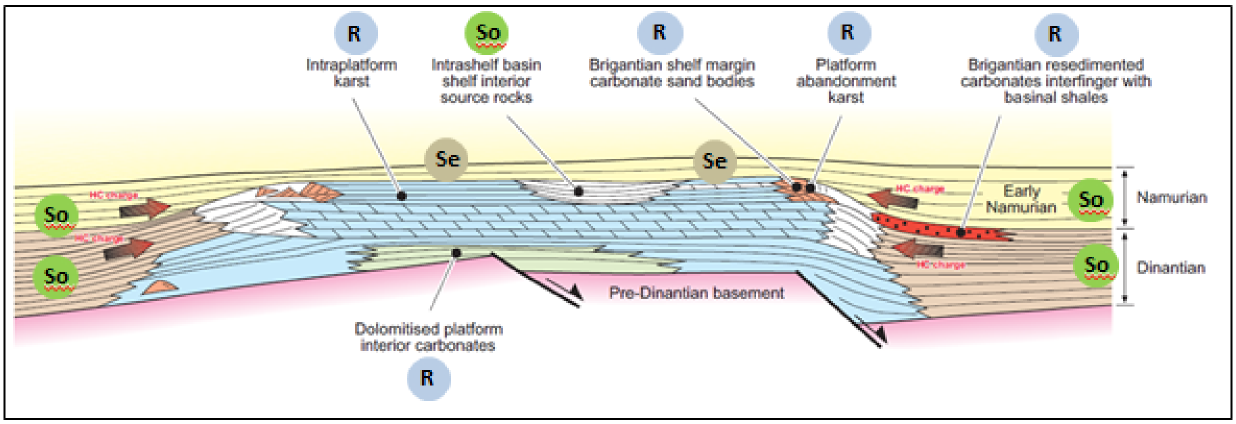
Discussion: Prospectivity review

Introduction

In order to discuss the prospectivity of the Dinantian carbonates onshore Northern Netherlands, the 4 key play elements need to be taken into account:

- Structure
- Reservoir
- Charge/Source
- Seal

The results from this study are discussed by these 4 play elements, and they are put together in a so-called "Italian flag". This figure displays each play element with their positive, negative and neutral indicators. After that a map with prospective areas is presented, accompanied with the key risks for these leads. Figure 1 displays the play concept and elements.



Structure	(faulted) carbonate platform
Source	Namurian / Dinantian shales (lateral migration)
Reservoir	karstified / fractured (Visean) limestone
Seal	Namurian shales (top / side seal)

Fig. 1: play concept and elements of the Dinantian carbonates (from EBN, 2012).
http://www.nlog.nl/resources/Posters/prospectfair2012/Poster8_Prospex%202012.pdf

Structure

The structures that might capture the hydrocarbons are the carbonate build-ups as presented in the chapter: ”Geometry of the Dinantian carbonate build-ups in the Dutch northern onshore“. They comprise: the flat topped horizontal platform Uithuizermeeden, the tilted and flat topped platform Fryslân (Tytsjerk part) and the convex build-ups/mounds Fryslân (Blija part), Luttelgeest and Muntendam (Bedum part) and undulating build-up Muntendam (Meeden part). See figure 2 for the outlines of these build-ups and figure 3 for a quick recap of the geometry as represented in the seismic.

Uplift of the Southwestern part of the study area, tilted the Fryslân platform while faulting isolated the Blija part from the Fryslân flat topped platform. The Hantum fault zone and the Lauwerszee Trough separated the carbonate build-ups in the West from the carbonate build-ups in the East. The Muntendam build-up is undulating /convex and is buried deeper than the other 3 build-ups (see figure 2). The Muntendam build-up might be of Devonian age. Better reservoir quality is expected in the progradation sequence on the slope of a Dinantian carbonate build-up during a highstand. The slope therefore can preserve hydrocarbons in a stratigraphic trap. The stratigraphy of the flat/carbonate build-up interior is very tight (as seen in the well results of UHM-02 and LTG-01) and might and might prohibit hydrocarbons present in the slope to migrate into the platform interior e.g. act as a seal.

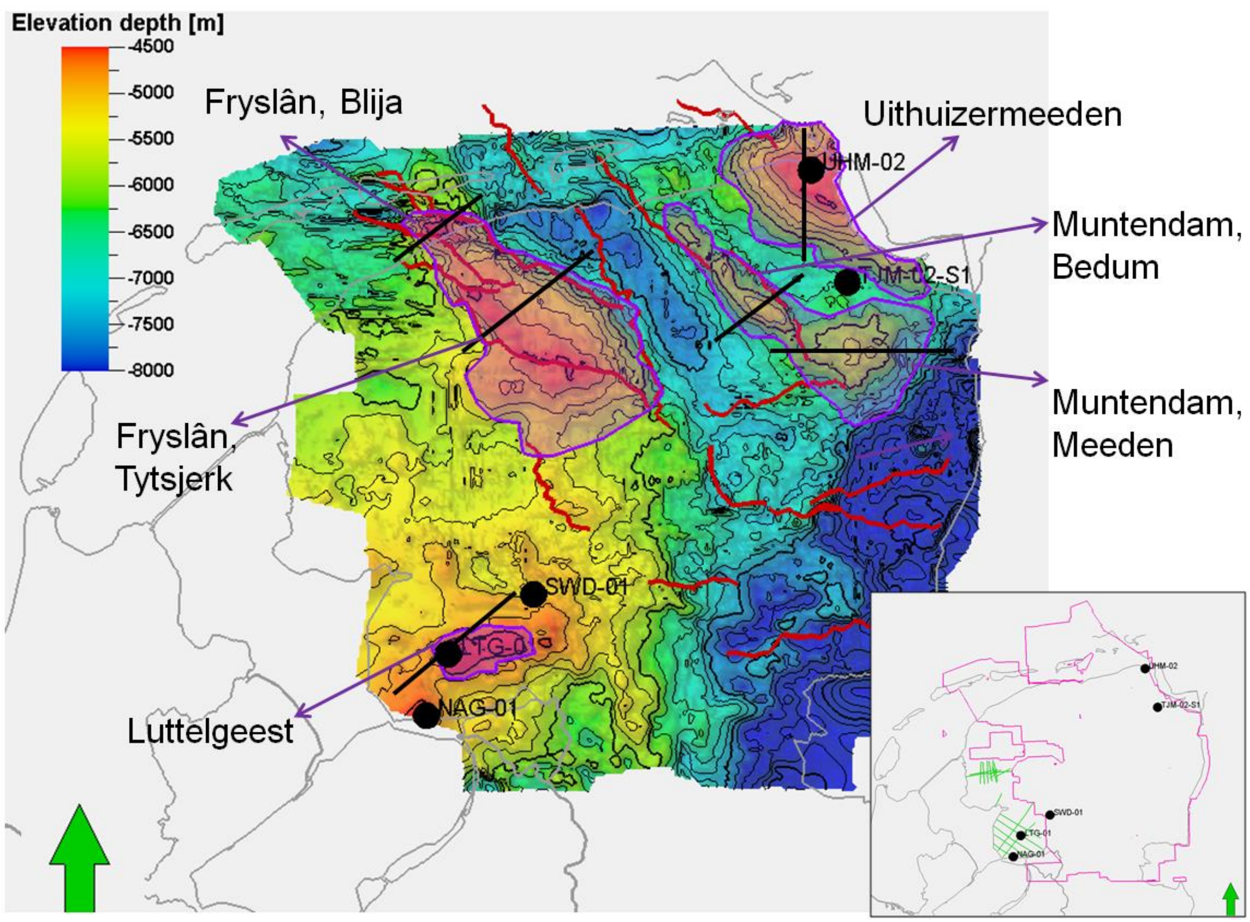


Fig. 2: The 4 studied carbonate build-ups in a depth surface. Red lines indicate faults, purple outlines indicate the carbonate build-ups as defined by onlapping features. Black lines indicate the placing of the cross sections of the seismics in figure3.

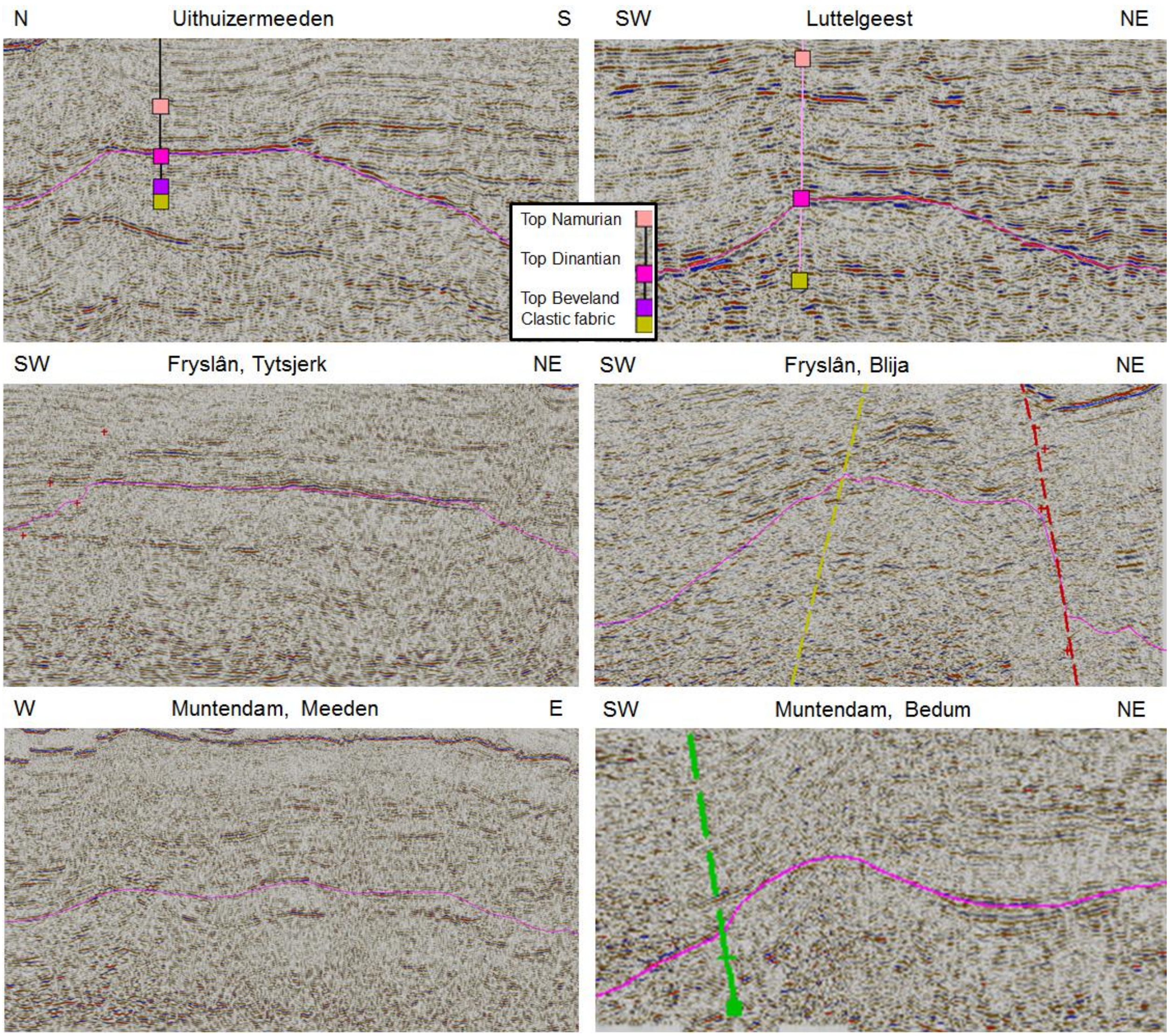


Fig. 3: Seismic sections in TWT(ms), location of the sections is indicated on figure 2. Uithuizermeeden: flat topped horizontal platform, 1580m thick. Luttelgeest: convex mound build-up, 550m thick. Fryslân (Blija): convex mound build-up, 1300m thick. Fryslân (Tytsjerk): tilted flat topped platform, 1300m thick. Muntendam (Meeden) undulating build-up, 1100m thick. Muntendam (Bedum): convex mound build-up, 1100m thick.

Reservoir

Core descriptions from both wells describe very tight limestone deposits (porosity less than 2 %), and fractures are mostly cemented. During a highstand progradation, on the slope of a Dinantian carbonate build-up, generates coarse grains (high energetic environment), steep slopes, angular grains (breccia) and fractures (when slopes become unstable after lithification).Good reservoir quality (4% porosity) of slope progradation deposits have been proven by the Tengiz oil field in Kazakhstan (Francis et al., 2008). Increase in angular/breccia deposits have been proven by the tilted and outcropping carbonate build-up in Sierra del Cuera in Spain (Verwer, 2008). These deposits have good reservoir quality (absolute numbers on porosity are not present, due to the fact that this was not the aim of the study).

Seismic response has been studied by use of UK Dinantian carbonate build-up analogues. Kirby and Evans (1999) recognize 2 distinct seismic facies: 1 a 'stripy' facies that correlates with deep marine carbonate deposits and s 'quiet' facies that corresponds with a shallow marine carbonate deposits underlain by clastics. These seismic facies have been found in the Dinantian carbonate build-ups of the Northern onshore Netherlands. The 'stripy' facies does not correspond with the lithology found in UHM-02 (deep marine versus shallow marine) the 'quiet' facies corresponds with the shallow marine deposits found in UHM-02. Data is limited and further research for seismic response of Dinantian carbonate build-ups is needed.

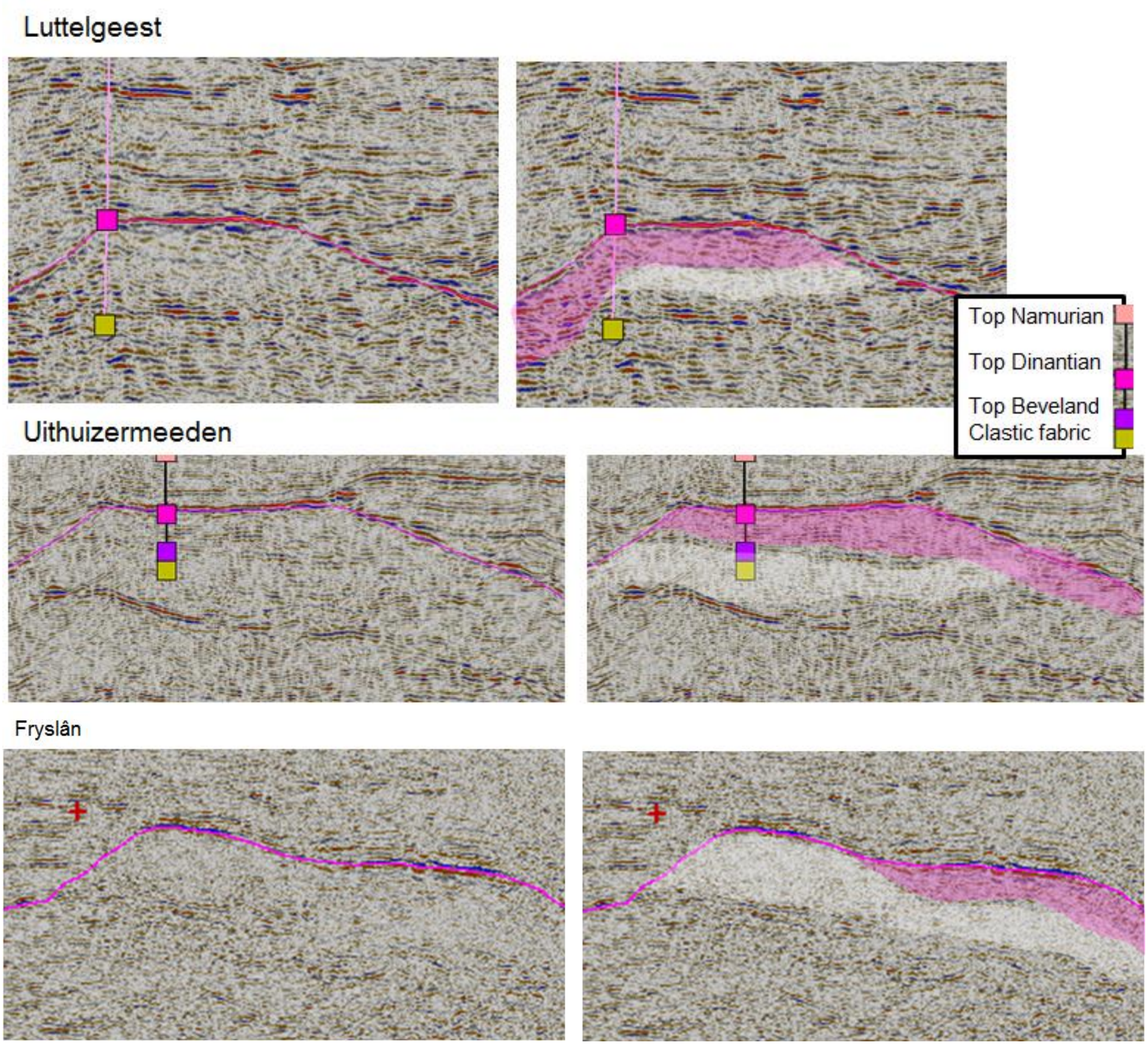


Fig. 4: *Seismic character of the Dinantian build-ups studied in this research. Pink color represents 'stripy' seismic facies and the white represents the 'quiet' seismic facies or more transparent character, as described by Evans and Kirby (1999) .*

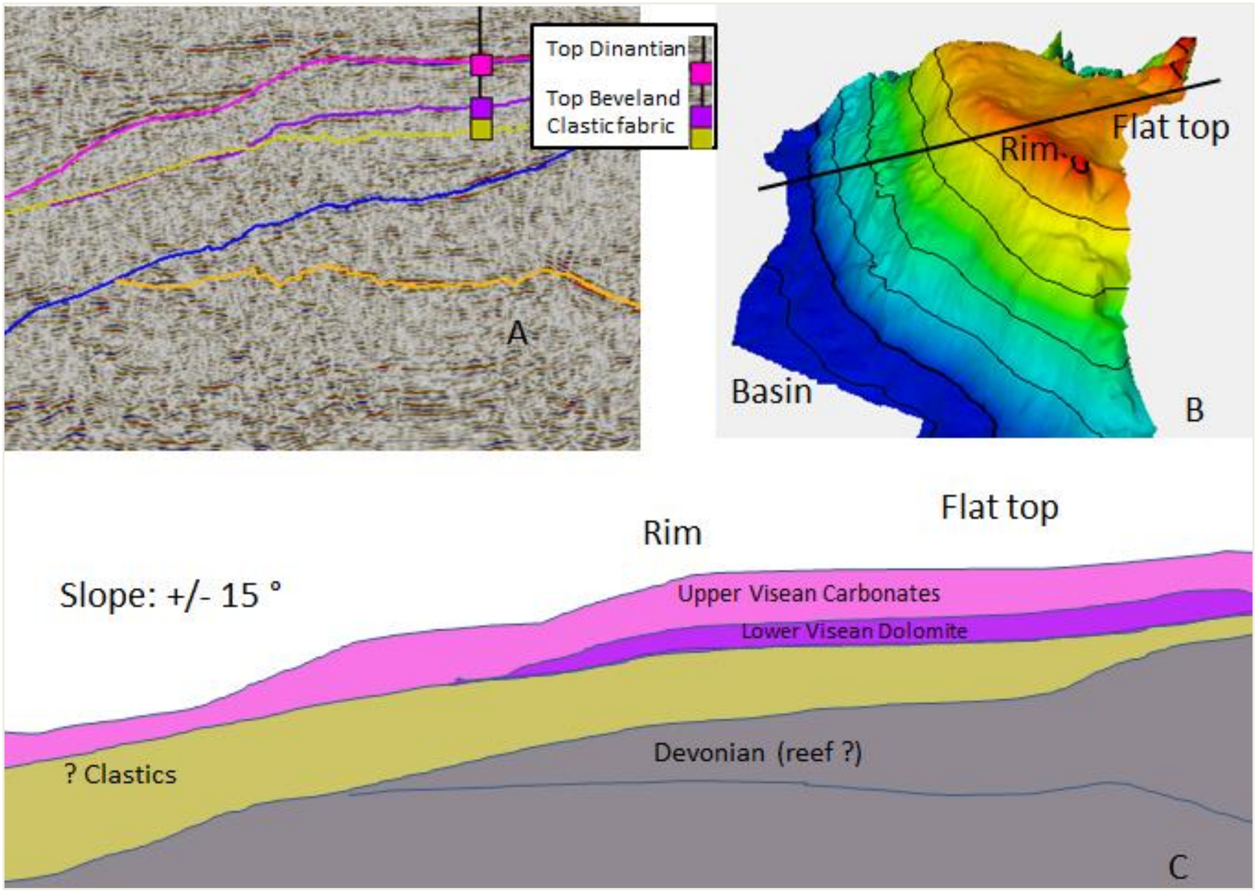


Fig. 5: Detailed seismic interpretation of Uithuizermeeden. The Beveland member consist of dolomite that is associated with a lowstand in the lower Visean. The upper Visean deposits consist of shallow marine carbonates associated with a progradational sequence during a highstand.

These facies also show signs of progradation sequences (see figure 4). In southern Belgium a major low stand is documented during Lower Visean, giving rise to dolomitization of the coarse grained limestones of the underlying sequences. Dolomitization is limited to carbonates stratigraphically positioned below a low stand in the Late Visean (Van Hulten and Poty, 2008). The dolomite of the Beveland member can be correlated to this lowstand. The Lowstand is followed by a highstand, which gives room for progradation. Figure 5 shows a detailed interpretation of the Uithuizermeeden flat-topped platform; progradation is recognized in this build-up. All these analogues (Tengiz, Sierra del Cuera, UK seismics, Belgian outcrops) tell us that good reservoir quality, in terms of primary porosity, should be searched for in the slope deposits of the Dinantian carbonate build-ups.

At the Tengiz oil field, the highest rate wells (10,000 to 30,000+ barrels/day) are located at the platform margin and within the slope. The slopes of this field are so important because primary porosity is good (progradation) and the slopes are highly fractured. The fractures are vertical and widened by dissolution (karstification processes) and increase permeability. As seen in figure 6; the seismic data at Uithuizermeeden shows discontinuities in the seismic at the slope, which might indicate faults with associated fractures. Karst features are mentioned in the well reports on thin section scale: dissolution of fractures, time equivalent infill (UHM-02), micritic zones with infill (LTG-01) and log responses indicate karst horizons and or open fractures. The fractures at the flat/interior of the platform were described in the core as cemented, whether the fractures at the slope are opened or cemented cannot be said for sure and further research is needed. Secondary porosity, mainly at the slope, may play an important role for reservoir quality.

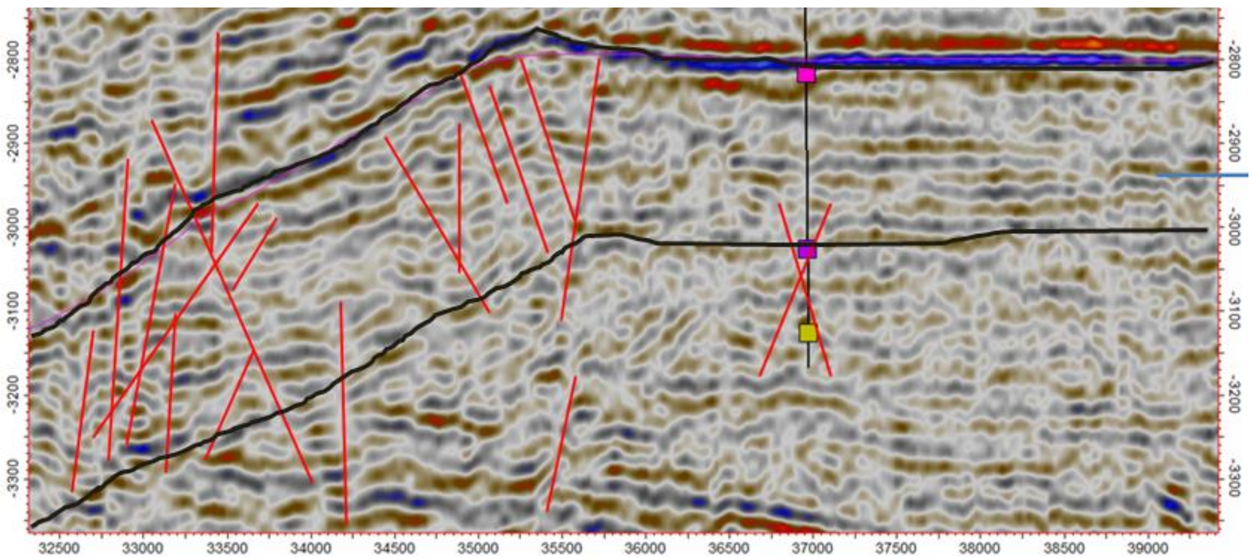


Fig. 6: Enlarged seismic section from figure 5 (same legend). discontinuities in the seismic might indicate faults with associated fractures. These continuities are most abundant on the slope and show the same orientation (vertical) as the Tengiz analogue in Kazakhstan.

Charge

The chapter “The geological history of the Dinantian in the study area (Northern onshore Netherlands)” describes the geometry of the Lauwerszee Trough. Origin and timing of this feature is hard to establish. In figure 7 a seismic line from Uithuizermeeden to Fryslân is displayed with the Lauwerszee Trough in between. The second seismic section is flattened on the base Zechstein to find out, whether the Lauwerszee Trough was already a deep at Dinantian times. It is impossible to state from seismic data whether carbonate build-ups were present and subsided along the Hantum fault zone (into the ductile domain), or whether carbonate build-ups were never present due to the deep marine environmental setting. The section shows that the Fryslân build-up is still tilted after flattening. From this it is concluded, that tectonism must have taken place during Carboniferous/Perm , which could have created an active deep. The Namurian deposits in the Lauwerszee Trough onlap the Dinantian carbonate build-ups, and they are assumed to comprise deep marine deposits, which could act as source rock charging the carbonate build-ups laterally. In that case carbonate build-ups closer to the Lauwerszee Trough would have a higher chance of containing hydrocarbons. LTG-01 and UHM-02 both have interbedded shale deposits of a few meters in thickness, in between carbonate deposits according to their core descriptions. Shale deposits within the structure might reach maturity and act as source rock for the carbonate reservoir zones. LTG-01 was dry and UHM-02 had a gas show with a 85% nitrogen content. Both wells experienced a temperature of 200 °C at TD, meaning that HC accumulations would become overcooked. High Nitrogen contents are very common for ‘old’ source rock. De Jager and Geluk (2007) state:

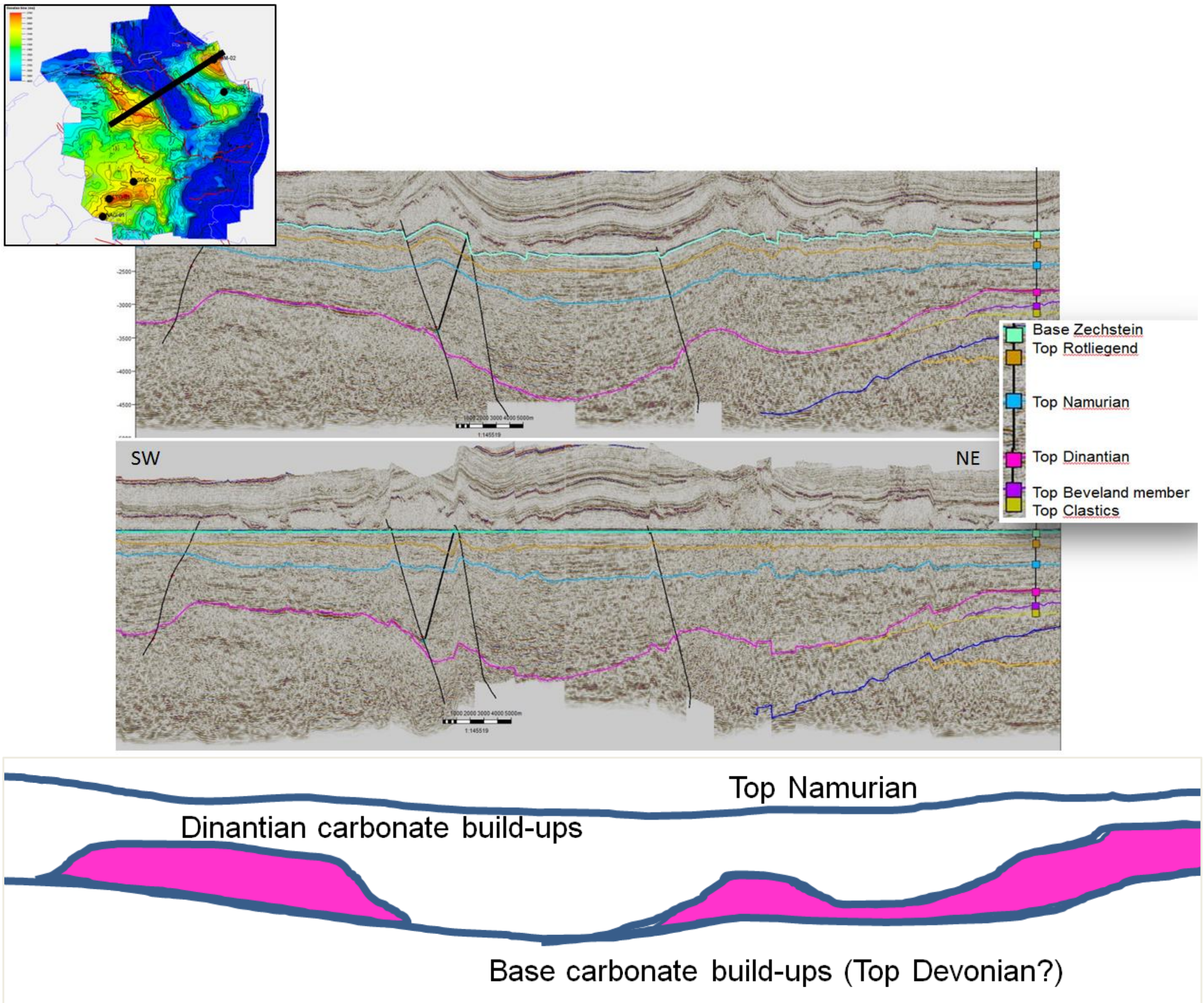


Fig. 7: *Seismic section Trough Uithuizermeeden, Muntendam and Fryslân. Mapped faults in black. Small square is the outline of the research area and shows the emplacement of the seismic section. Top seismic section is in ms TWT, bottom seismic section is flattened on base Zechstein.Underneath a schematic section Dinantian carbonate build-ups on a presumable Devonian paleotopography at the end of the Carboniferous.*

"Source rocks for gas occur in basal Namurian organic rich shales. In most places these source rocks became overcooked during deep pre-Kimmerian burial. The Namurian is thought to have contributed significantly to the nitrogen charge, which is mainly expelled at much higher temperatures than hydrocarbon gas. The gas quality in the various reservoirs shows distinct variations. The most abundant non-hydrocarbon component is nitrogen. Differences in nitrogen content, from almost zero to more than several tens of percent, can be a result of differences in source rocks, but also of differences in their heat-flow and burial histories. Until the Late Jurassic, heat-flow rates were high and the Westphalian coals were expelling hydrocarbon gas while the much deeper Namurian shales expelled nitrogen (see figure 8). This phase of charge was therefore in most places relatively rich in nitrogen. It ceased during times of uplift and significant erosion, e.g. during the Late Jurassic. Thus, in areas with present-day charge, gas fields generally contain less nitrogen than in areas with only 'old' charge. The gas with the anomalously high nitrogen content of 30% in block E12 was probably generated from Namurian source rocks." (De Jager and Geluk, 2007. And references therein).

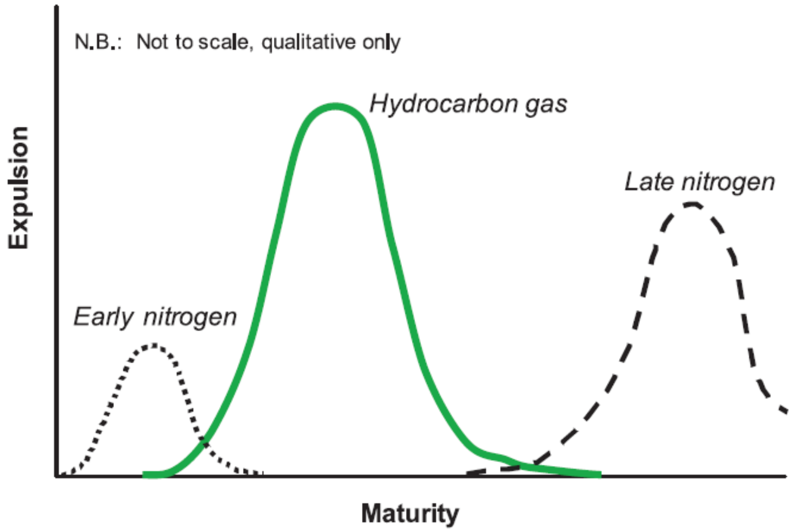


Fig. 8: Expulsion of hydrocarbon gas and nitrogen versus maturity. Apart from a minor early phase of generation, most nitrogen is expelled at much higher maturities than hydrocarbon gas. (De Jager and Geluk, 2007).

Source rock potential for Dinantian carbonates has been studied, and Schroot et al., 2006 states: "The transition from the Dinantian to the Namurian is expressed by a marked drop in carbonate sedimentation. This resulted in clay sedimentation Throughout NW Europe. It is suggested that these shales have been draped over the pre-existing Dinantian topography (see figure 9). These shales have proven high TOC values (e.g. Geverik Member). The main intervals with initial high source rock potential are found near the base Namurian (Geverik Mb equivalent) and within the Namurian. However, these source rocks are currently over-mature. Burial history reconstruction must identify at what moment in geological history generation and expulsion of hydrocarbons took place. Generation will have occurred early in geological history, mainly due to a higher heatflow at several instances in time. Generation of hydrocarbons from the kerogen in the Namurian and older source rocks took place already during the Carboniferous. The transformation was completed at the end of the Carboniferous; no more hydrocarbons could be generated. The prospectivity of the Dinantian in the study area is therefore strongly dependent on the preservation of the hydrocarbons from the Carboniferous onwards. This implies that accumulation space, the reservoir, and a good seal were present at the end of the Carboniferous and were preserved Throughout geological times. Source rocks with an initial excellent/good are currently overmature." (Schroot et al., 2006. And references therein).

The core descriptions of UHM-02 show indications for uplift, also the Southwestern part of the study area has been uplifted as discussed in a previous chapter. This means that burial depth and therefore temperatures were even higher, which is a negative factor for charge for the risk at overcooking is even greater.

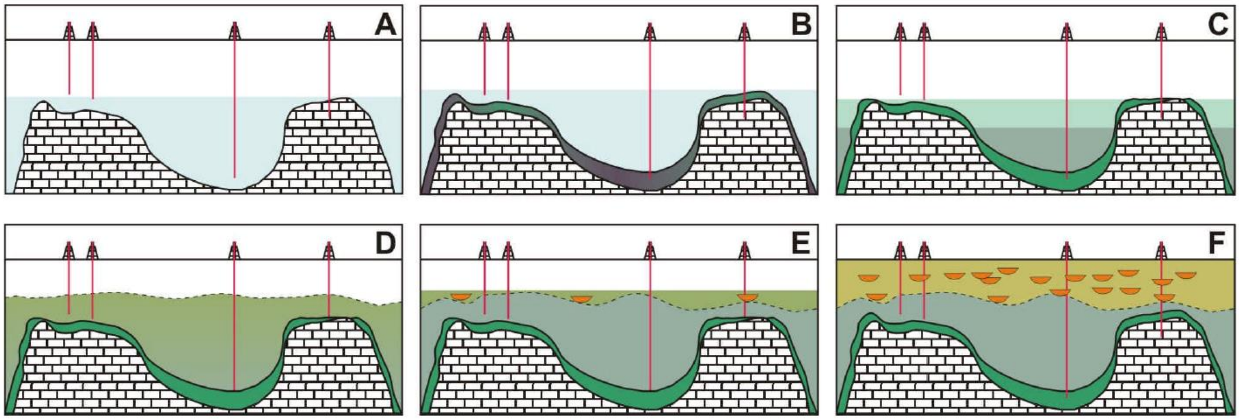


Fig. 9: Development of the Namurian, including the "Geverik draping" event. A=Late Dinantian; B=Pendleian (Geverik Mb and equivalents); C=Early Arnsbergian (Epen Fm.); D=Late Arnsbergian (unconformity); E=Chokerian; F= Chokerian – Yeadonian ("sandy" Epen Fm. and base Baarlo Fm)

Age of units	Area	Type	TOC median [%]	TOC max [%]	Maturity [%Rr]	Initial SR potential	Present-day SR potential
Devonian	Area 1	III + (II)	0.5	2.9	1.5 - 3.0	fair	low
	Area 2	III + (II)	0.2	5.8	0.7 - 1.5	fair	fair to low
	Area 3 & 4	(II)	0.7	1.1	4.0 - 5.0	low to fair ?	low
Dinantian	Area 1	III + (II)	0.6	16.9	0.8 - 2.0	fair	fair to low
	Area 2	III + II	1.2	68.2	0.5 - 2.0	fair to good	fair
	Area 3 & 4	(II)	2.7	8.7	4.0 - 5.0	low to fair ?	low
Top Dinantian - Base Namurian	Area 1	II + III	2.5	12.1	1.0 - 1.2 (NW)	good to fair	fair
					3.0 - ? (SE)	excellent	low
	Area 2	III + (II)	3.2	6.0	0.5 - 2.0	good	good
	Area 3 & 4	II	3.5	6.2	4.0 - 5.0	excellent	low
Namurian	Area 1	III + II	1.1	4.5 (21.5)	0.5 - 1.5 (NW)	fair	fair
					2.3 - 5.0 (SE)	fair	low
	Area 2	III + (II)	2.2	72.1	0.5 - 2.6	fair	fair
	Area 3 & 4	III + II	1.3	77.1	1.5 - 4.5	good	low

Table 1: Summary table for the evaluation of the potential source rocks (SR), area 3 and 4 lie within the research area of this study. Of course, the results described above are biased, due to the limited number of wells at selected locations (mostly present-day structural highs). Based on the preferred block and- basin setting, other pre-Westphalian source rocks may be present. However, there are no direct indications for this since these were never drilled. Nevertheless, oilprone source rocks with high organic matter content can be presumed to be deposited in the "deeper" intra-platform basins that were characterized by restricted circulation(Schroot et al., 2006).

Namurian shale source rocks are associated with high Nitrogen content, there is a great risk at overcooking of these source rocks. Overall the gas quality is expected to be low, UHM-02 supports this theory. In order to designate an area as prospective, abundant quantity of gas must be present. The Geverik member is a known source rock and it is present in the well UHM-02, above the Carbonate succession. If the Geverik member does indeed represent a draping event, it also covers the slope of Uithuizermeeden, and could have charged the better reservoir at the slope. All the other wells in the study area have not encountered the Geverik member, NAG-01, TJM-02-S1 and SWD-01 may have reached TD before the Geverik member could be detected. Nevertheless the draping event cannot be validated and it cannot be concluded whether Fryslân and/or Muntendam could have been charged by this member. Prospective areas lie within the range of either the Lauwerszee Trough or near the (proven presence of) Geverik member.

Seal

The discontinuities found in the seismic, which might indicate faults with associated fractures, at the slope of Uithuizermeeden, may be a negative factor for sealing capacity of the above lying shale deposits. LTG-01 is overlain by shaly deposits and UHM-02 is overlain by shales (Geverik member). The presence of the Geverik member encountered in well UHM-02 is a good sign for seal capacity; source rocks act as good seals. 'Old' charge implies that a good seal was present at the end of the Carboniferous and hydrocarbons were preserved throughout geological times, this is highly unlikely for preserving a seal that long since it becomes brittle and leaches.

Conclusions

All the play elements discussed are summarized and put together in a so-called Italian flag in figure 10. Green indicates positive factors contributing to the prospectivity, white indicates neutral factors contributing to prospectivity and red indicates negative factors contributing to prospectivity.

From this study it can be concluded that:

- Reservoir quality is probably best at the slope of a carbonate build-up
- Luttelgeest and Uithuizermeeden have been tested and they gave negative results
- Muntendam and Fryslân have a higher chance for charge, as they are close to the Lauwerszee Through.
- The slope of Uithuizermeeden has a better possibility for charge than the flat, as the Geverik member might be charging this stratigraphic trap.
- The Fryslân structure is more promising than Muntendam, for the structure is shallower and therefore temperatures might be lower

Based on the Italian flag and these conclusions; 5 prospective areas have been identified (see figure 11) for further exploration studies.

italian flag play element	Positive factors	Neutral factors	Negative factors
structure	progradation tilted Fryslan undulating Muntendam convex Luttelgeest	faulting along the Lauwerszee Through	depth conversion due to limited data
reservoir	faults/fractures at slope progradation	limited signs of karst in UHM-02 and LTG-01 gas show in UHM	Interbedded shale units UHM-02 and LTG01 very tight
charge	deep marine deposits in Lauwerszee Through Interbedded shale units Geverik member present UHM-02	Geverik member present in WSK-01	high temperatures UHM-02 and LTG-01 UHM 85% Nitrogen LTG dry Source rock unknown (?) Namurian considered bad source rock (N) Dinantian source rock overcooked
seal	build-ups are overlain by shales UHM-02 build-ups are overlain by shaly deposits LTG-01 Geverik member present UHM-02	Namurian shales act as seal elsewehere	faults/fractures at slope active seal since pre-Carboniferous charge

Fig. 10: Italian flag with all the play elements and results from this study

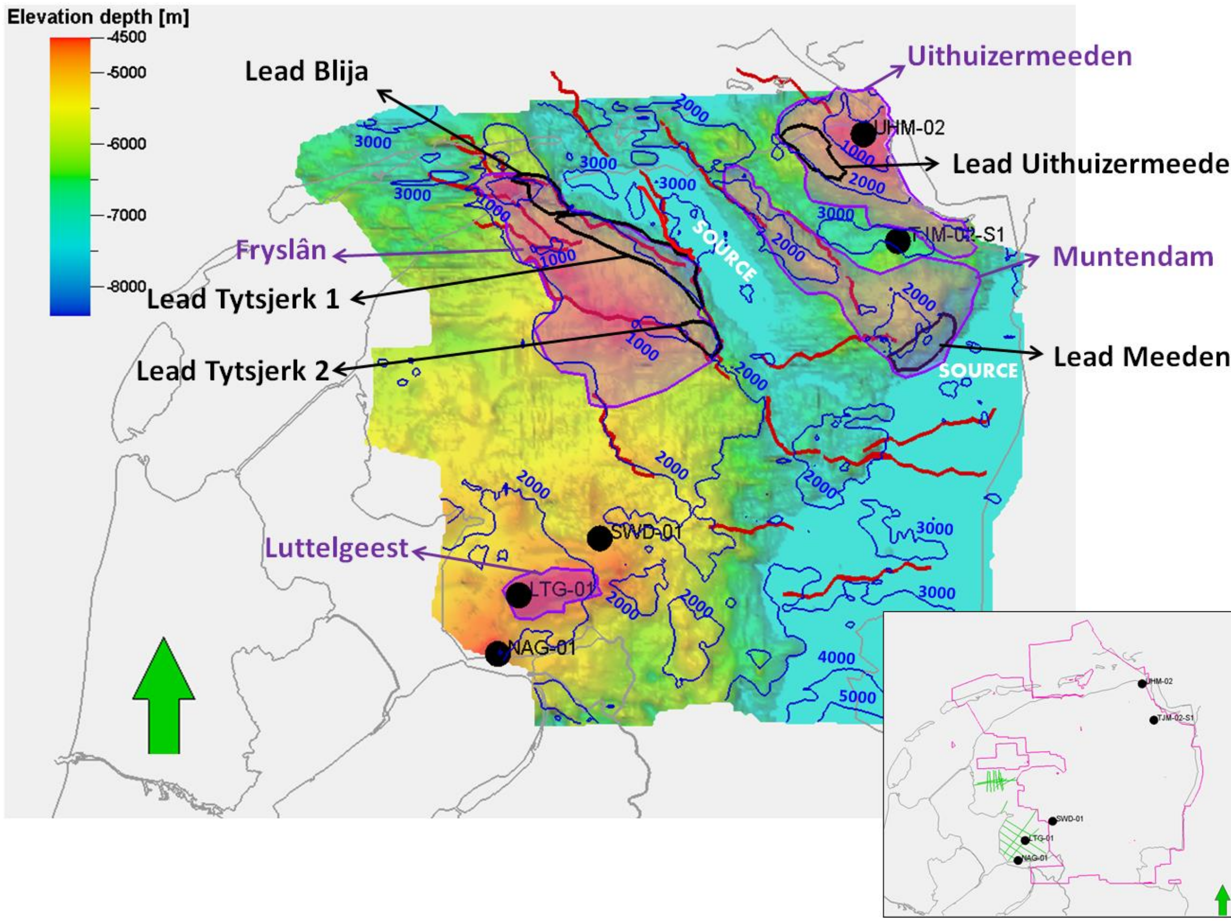


Fig. 11: Play map. Top Dinantian in depth. Purple polygons are the carbonate build-ups, the black polygons are leads, the red lines indicate faults, the blue contours are the thickness of the overlying Namurian deposits and places for possible source rock are indicated with: SOURCE.

The associated key risks for all these leads are (in order of highest risk to lower risk):

1. High temperatures leading to over-mature source rock, and drilling hazards
2. Gas quality (high Nitrogen content) as a result
3. Leaching by faults (seal must have been present at the end of Carboniferous and must have been preserved)

Lead Blija, Tytsjerk 1 and 2: On the slope of the Fryslân flat-topped platform, where progradation creates primary porosity and fracturing creates secondary porosity and permeability. Near the Lauwerszee Trough for charge. Namurian shales may act as an seal.

Lead Meeden, where progradation increases primary porosity and fracturing may increase secondary porosity (better reservoir quality). This carbonate build-up might be of Devonian age, when carbonate production was based on reefbuilders (that gives a better reservoir, but a bigger uncertainty on where to best drill an exploration well). The Muntendam structure is deeper and probably hotter than the other build-ups, which is a negative factor for charge.

Lead Uithuizermeeden, where progradation creates primary porosity and fracturing creates secondary porosity (better reservoir quality than the flat). Charge may have come from the Geverik member that was draped on the slope. And the tight flat can act as a stratigraphic seal.

Geothermal energy

The reservoir quality of the Dinantian carbonates Northern onshore Netherlands is such that water can flow. Uithuizermeeden has been tested and water flow was 103m^3/Day, in order to make this reservoir valuable for geothermal energy a flow of 100-150 m^3/hour is needed. When an exploration well will be drilled at the slope, reservoir quality is expected to improve.

UHM-02 and LTG-01 reached their TD at ~5000m (TVD), which in geothermal energy is referred to as “ultra-deep”. Ultra-deep geothermal energy can be acquired by Enhanced Geothermal Systems (EGS), this system is not in use yet, but test locations are present in Basel, Soultz-sous-Forêts en Landau.

These ultra-deep rocks are highly compacted and porosity and permeability is often too low. EGS uses reservoir stimulation by injecting cold water into the hot formation. The temperature difference and the high pressure of this injection fractures the reservoir rock, which improves porosity and permeability. Also the flow of water with a low pH (with dissolved CO_2) and/or fresh water (change in salinity) might stimulate further karstification during the water flow, when the reservoir is used for geothermal energy.

UHM-02 and LTG-01 reached TD at 200 °C, which is ideal for a binary electricity generating system (see figure 12). In Iceland, Indonesia and New-Zealand electricity is already generated by geothermal heath. In these regions very high temperatures (200 °C) are relative close to the earth surface (1000m). In the Netherlands, these temperatures are reached at much greater depths, and therefore the term ultra-deep geothermal energy is used.

All information on geothermal energy is from (Kramers et al., 2012).

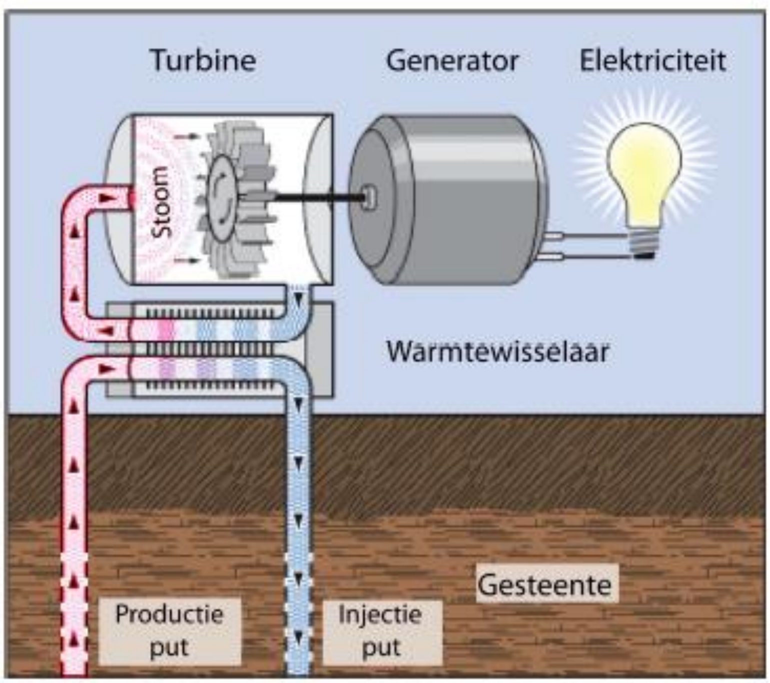


Fig. 12: geothermal energy generated by a binary electricity system. (Kramers et al., 2012)

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Appendices

Appendix I

2 Well sections of wells that reached Dinantian aged rocks
Carbonate limestones onshore Netherlands

Appendix II

3D seismic interpretation of the Dinantian
Netherlands Northern onshore

Appendix III

2D seismic interpretation of the Dinantian in the
CAL-GT-01 Area, A complex tectonic regime

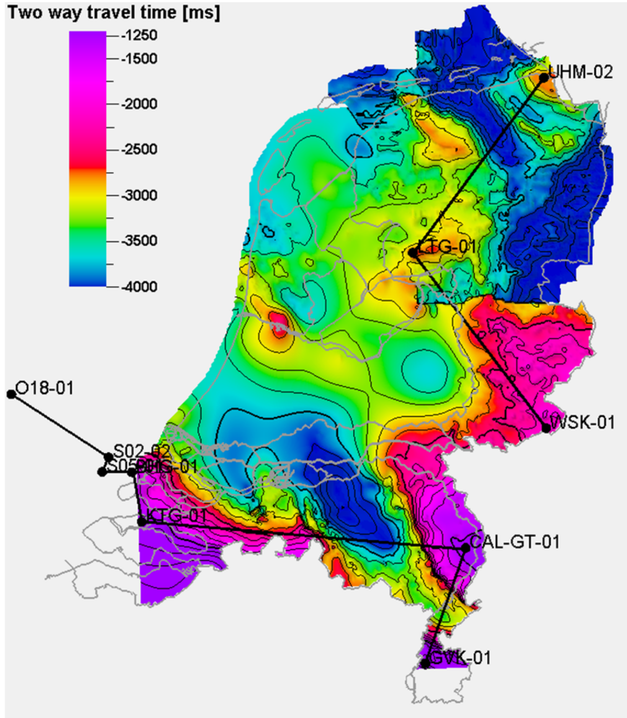
Appendix IV

Log Information of the California GT-01 well
A complex tectonic regime

Appendix I

2 Well sections of wells that reached Dinantian aged rocks
Carbonate limestones onshore Netherlands

Nynke Hoornveld



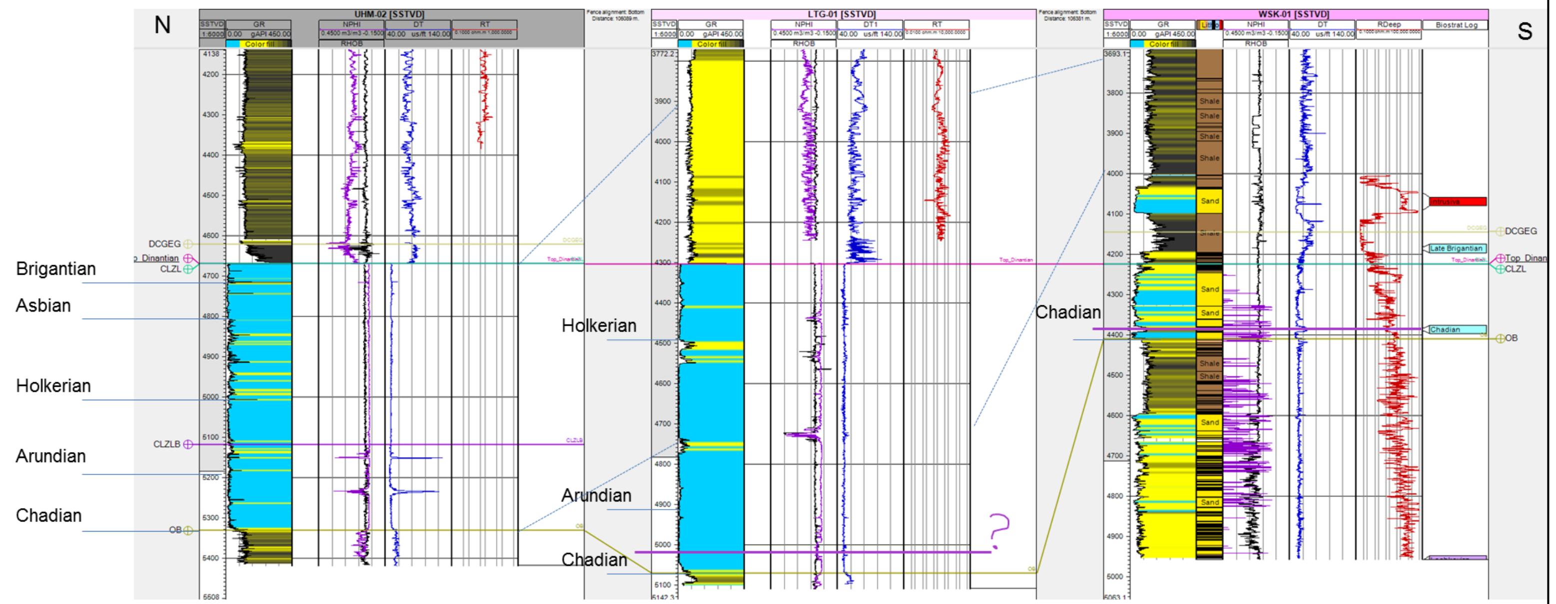
Well section North
UHM-02

LTG-01

WSK-01

Combined TWT surface of Top Dinantian. Northern onshore is mapped in this study. the Southern onshore part has been mapped by TNO (Ed Duin) and represents work in progress.

Well section South
O18-01 S02-02 S05 BHG-01 KTG-01 Cal-GT-01 GVK-01

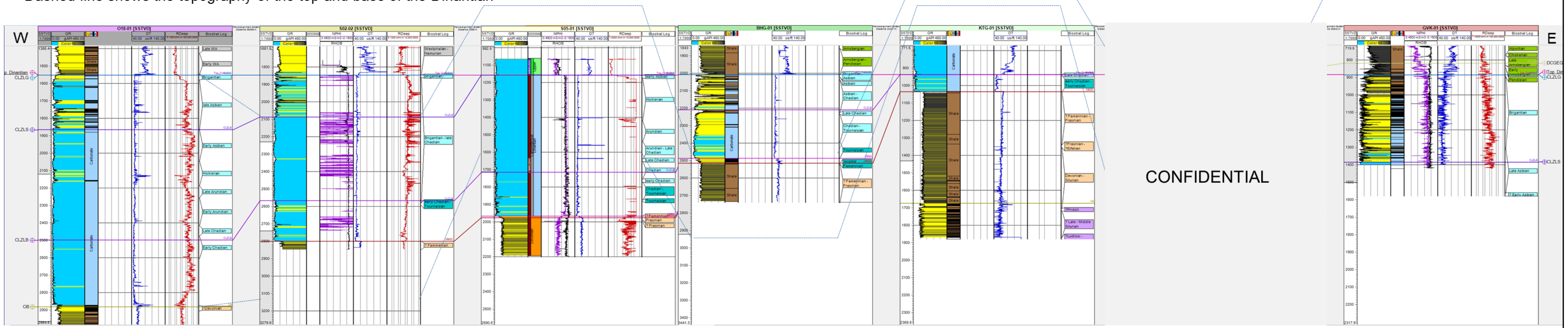


Chronostratigraphic interpretation come from the composite log at NLOG.nl.
Spikes in the logs in the Beveland member could be related to karstified zones and/or fractures/faults.

Chronostratigraphic interpretation from Van Hulten (2012) and information on NLOG.nl. Dolomites are registered in the mudlog underneath the purple line with the question mark. Peaks in de neutron density logs could be related to vuggy porosity.

Chronostratigraphic interpretation come from NLOG.nl.
The Beveland member is present according to petroplay (2006): they refer to it as Dinantian 1.

Dashed line shows the topography of the top and base of the Dinantian



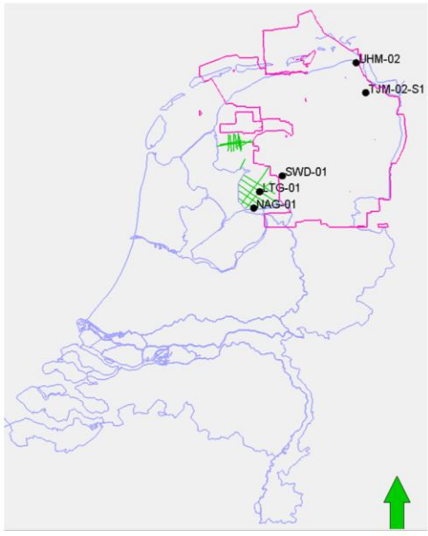
Tournaisian section is absent in the Dinantian carbonate build-ups encountered in the Northern wells UHM-02, LTG-01 and WSK-01, contrary to the South where both Visean and Tournaisian are present in all wells. This could be related to climate change in these periods, affecting the carbonate build-up. It could also be related to the paleotopography that differed very much in the South due to the presence of the London-Brabant Massif and the Variscan front. The Southern section shows massive uplift and erosion at some places. The wells in the Southern section mostly comprise the Beveland member, the Schouwen member and the Goeree member, whereas the Northern ones only have a thin Beveland (UHM-02) or no Beveland present (LTG-01 and WSK-01).

Appendix II

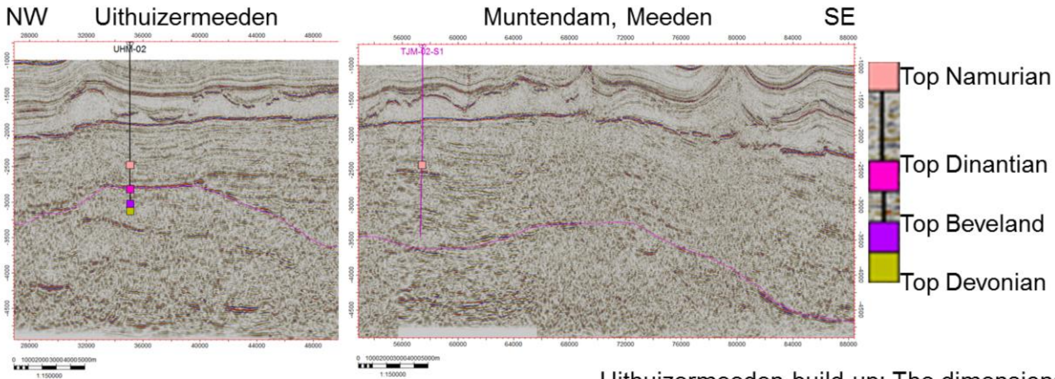
3D seismic interpretation of the Dinantian

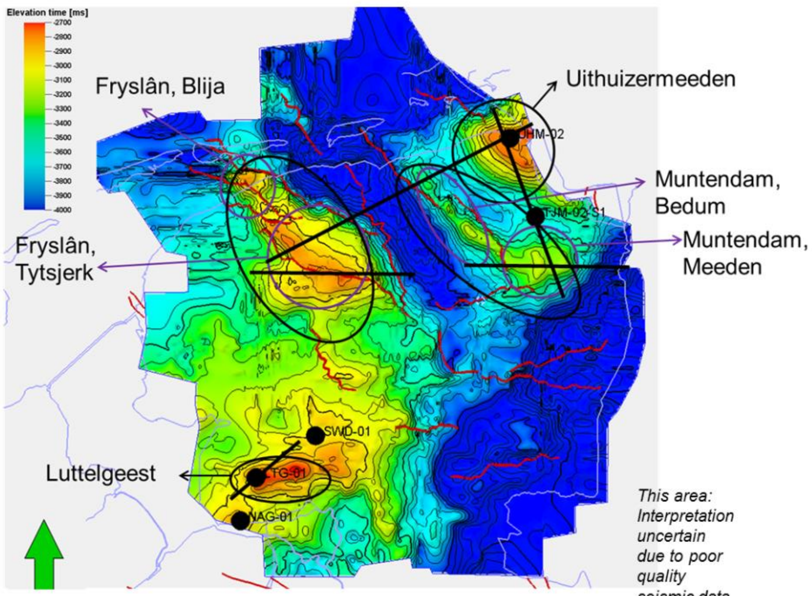
Netherlands Northern onshore

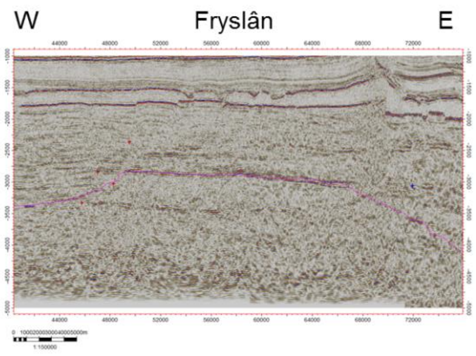
Nynke Hoornveld



Outline of the Netherlands with the data used in this study. Pink = outline of the 3D seismic merged TerraCube. Green lines = 2D seismic lines. Note that only wells: UHM-02 and LTG-01 reached Dinantian rocks. Other wells reached TD in Namurian.







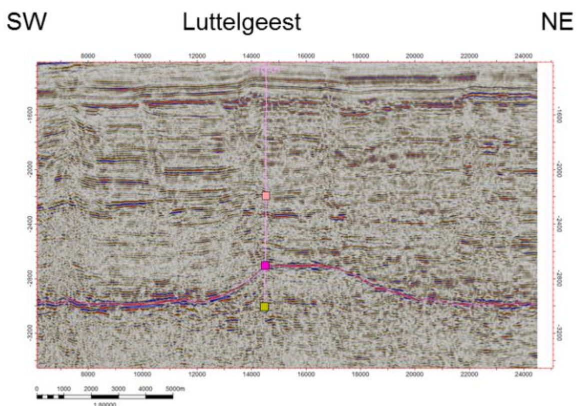
Fryslân build-up:

Fryslân, Tytsjerk	N-S	W-E
Build-up base depth	3300-3700 ms TWT	3300-3700 ms TWT
Build-up top depth	2800-3150 ms TWT	2800-3150 ms TWT
Build-up base length	30 km	26 km
Build-up top length	24 km	15 km
Base geometry	Flat, dipping in Westward direction	
Top geometry	Flat, slightly dipping towards NE	

Luttelgeest build-up has a W-E striking geometry.

Luttelgeest	N-S	W-E
Build-up base depth	3000 ms TWT	3000 ms TWT
Build-up top depth	2700 ms TWT	2700 ms TWT
Build-up base length	7,5 km	20 km
Build-up top length	3 km	14 km
Base geometry	Flat	
Top geometry	Convex, with flat intervals,	

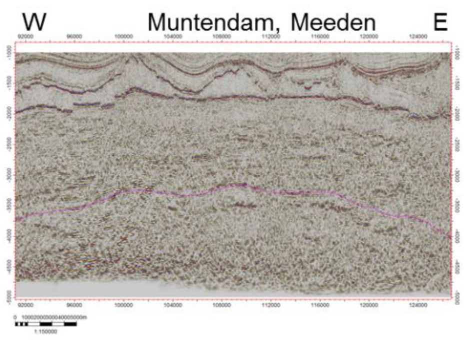
Westward extension of the platform is uncertain due to lack of seismic data.



Uithuizermeeden build-up: The dimensions are poorly constraint due to limited seismic data across the German border.

Uithuizermeeden	N-S	W-E
Build-up base depth	3500 ms TWT	3500 ms TWT
Build-up top depth	2800ms TWT	2800 ms TWT
Build-up base length	21 km	At least 20 km
Build-up top length	At least 7 km	At least 7 km
Base geometry	?	
Top geometry	Flat and horizontal	

The build-up possibly extends NE wards.



Muntendam, Meeden build-up:

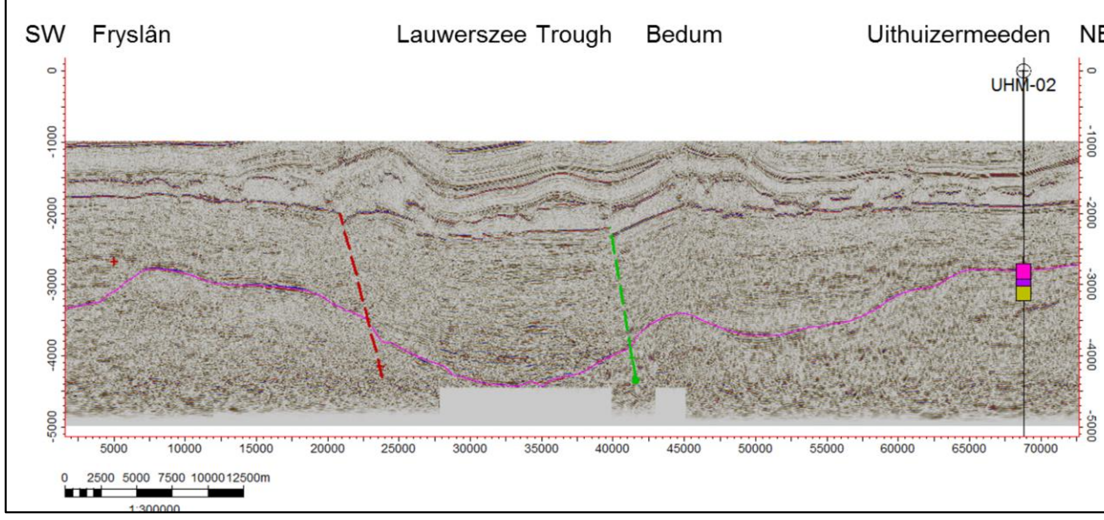
Muntendam, Meeden	N-S	W-E
Build-up base depth	3500 ms TWT	3500 ms TWT
Build-up top depth	Around 3200 ms TWT	Around 3200 ms TWT
Build-up base length	16 km	20 km
Build-up top length	10 km	13 km
Base geometry	?	
Top geometry	Undulating	

The Muntendam build-up is divided in two parts: Meeden and Bedum. Bedum forms a "rim" that extends NW wards around the Uithuizermeeden build-up, with onlap at the east and west side and a deep of 4400 ms TWT in between.

Muntendam, Bedum	N-S	W-E
Build-up base depth	3800-4400 ms TWT	3800-4400 ms TWT
Build-up top depth	Max. 3300 ms TWT	Max. 3300 ms TWT
Build-up base length	30 km	7,5 km
Base geometry	?	
Top geometry	Convex	

	Uithuizermeeden	Fryslân	Muntendam	Luttelgeest
Build-up base	6250 m	5600 m	6600 m	4850 m
Build-up top	4670 m	4300 m	5500 m	4300 m
Build-up thickness	1580 m	1300 m	1100 m	550 m
Build-up length	21 km	45 km	40 km	20 km
Build-up width	20 km	26 km	13 km and 7 km	7,5 km

	Flat-topped platform	Mound
Uithuizermeeden	x	
Muntendam, Meeden		x
Muntendam, Bedum		x
Fryslân, Tytsjerk	x	
Fryslân, Blija	x	
Luttelgeest		x



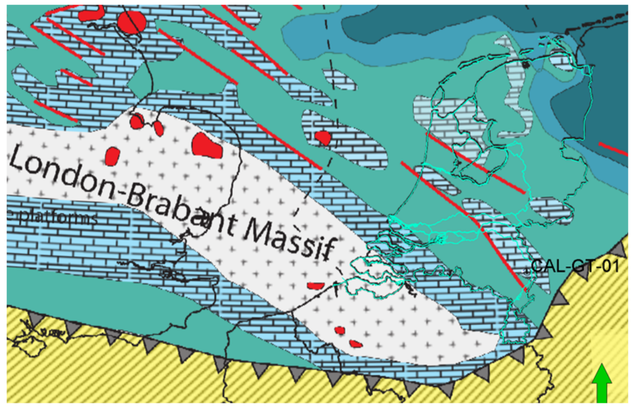
The South-Southwest area has been uplifted resulting in the tilting of the Fryslân flat-topped platform. The North-Northeast Dinantian carbonate build-ups were growing on a paleotopography. The Hantum fault zone has been active since at least Dinantian times creating a deep basin filled with marine shale deposits of Dinantian and Namurian age. The geothermal gradient is estimated to be 37,7°C/km allowing for ductile deformation and maybe even maturation of the potential source rock. Deep marine shales are often organic rich material and can provide source rock for the adjacent carbonate build-ups.

Appendix III

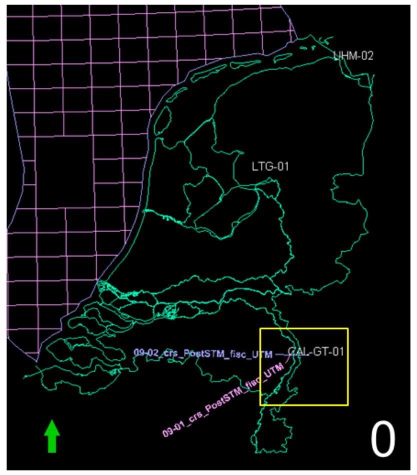
2D seismic interpretation of the Dinantian in the California GT-01 Area

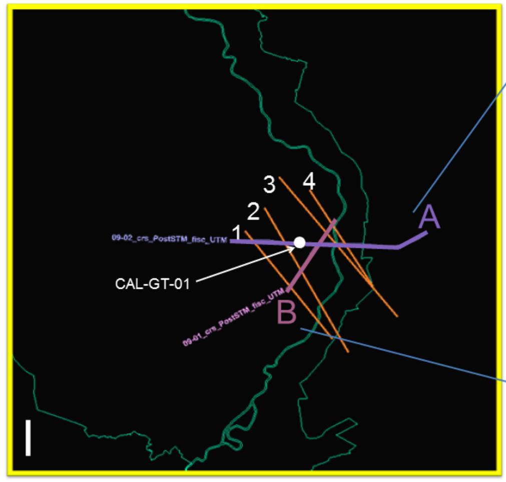
A complex tectonic regime

Nynke Hoornveld



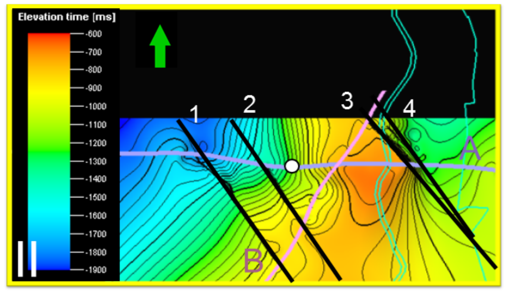
Paleotopography of the Dinantian, with carbonate platforms (bricks notation). And a black shale basin (dark green) in the North of the Netherlands. Also pointed out: the suture line of the Variscan front (thrust notations). Figure from: van Hulten 2012.

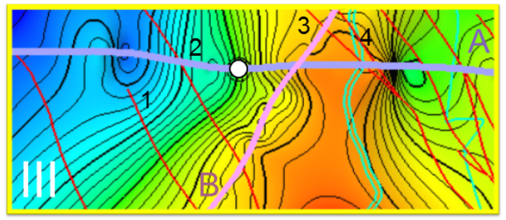


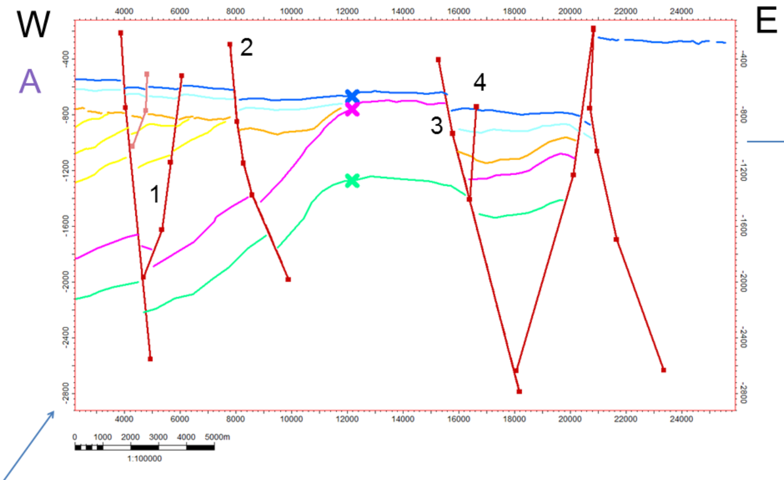


0 Outline of the Netherlands with the placing: of the seismic lines (A&B), of the CAL-GT-01 well and of the yellow square, which indicates the zoom I, II and III.
I Placing of the seismic lines (A&B), the well and the interpreted regional faults. Arrows point to the seismic lines and their interpretation.
II Surface made from the seismic interpretation in TWT (two way travel time; milliseconds), with interpreted regional faults.

III Same Surface and same scale as II, with interpreted regional faults from TNO.
Discussion: Does fault 1 extend in seismic line A?

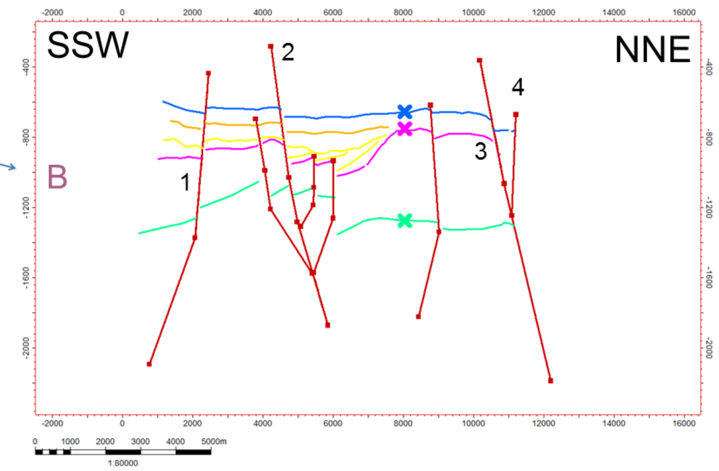


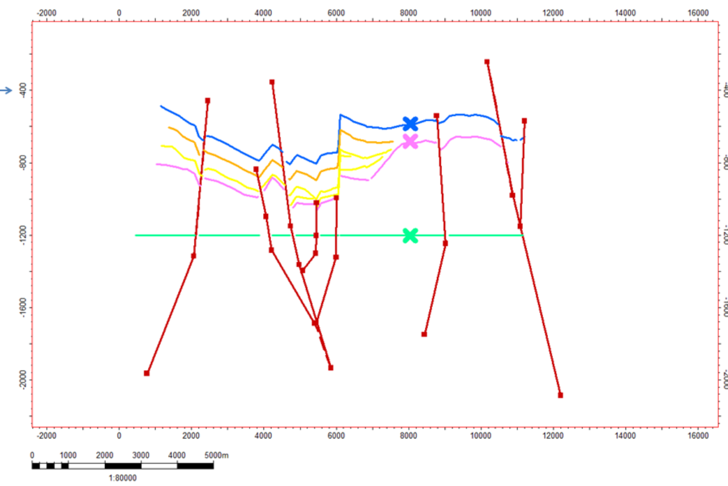




Note 1: Maybe fault 1 accomodates rotation, when it extends into seismic line A (compare the depth of the top Dinantian and the offset along the fault)).
Note 2: Cal-GT-01 is very different from the Northern onshore of the Netherlands, because the Variscan front is nearby.

Interpretations flattened on base Dinantian. Discussion points:
1: Is this a platform structure?
2: Where and when did erosion take place?
3: How deep was it burried and could the karstification be due to faulting/fracturing?





Tectonic setting and geolocical history

The area has experienced 4 phases of deformation as interpreted:

1. Extension in the late Devonian, which formed horsts and grabens (pure shear).
2. Variscan Orogeny in the Carboniferous, which formed strike-slip or wrench faults.
3. Variscan Orogeny in the Carboniferous, which caused inversion of earlier faults.
4. Extension in the Tertiary, which formed tilted blocks (simple shear).

Depth in TWT (ms) and distance in m.

Legend

	STRATIGRAPHY		Base of formation
	strong reflector		
N	north sea group	Tertiairy	
CK	chalk	Cretaceous	
RB	bundzandstein	Triassic	
ZE	zechstein	Permian	
DC	Limburg group/Namurian	Carboniferous	
CL	carbonate limestone/Dinantian	Carboniferous	

Appendix IV

Log Information of the California GT-01 well

A complex tectonic regime

Confidential