

The seismic sedimentology of syn-rift fluvial geothermal reservoirs: Insights from the West Netherlands Basin

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ABSTRACT

Fluvial sandstone reservoirs are among the most promising targets for geothermal exploration projects, making them essential in the energy transition. The heterogeneity of these reservoirs, particularly when syn-tectonic, can pose significant challenges for reservoir characterisation and, consequently, for planning of geothermal exploitation. A detailed understanding of their evolution, architecture, and spatial distribution, especially in relation to major tectonic structures, is therefore essential for effective risk mitigation. In this sense, image processing is essential for improving interpretative tools that detect heterogeneities in seismic data, which is crucial for accurately characterising sandstone reservoirs and reducing associated uncertainties. The comprehensive subsurface data available for the West Netherlands Basin, along with its growing geothermal industrial sector, makes it an excellent area to study fluvial sandstones deposited in a rift setting. Using available 3D seismic reflection data, seven distinct seismic facies were identified within the basins' main syn-rift Late Jurassic to Early Cretaceous geothermal reservoir, allowing a detailed interpretation of its heterogeneous depositional environment, further aided by the Root-Mean-Square (RMS) amplitude extraction technique. High-connectivity stacked channel intervals, found in both high-energy multi-channel river and delta-plain deposits, show the highest geothermal potential. In contrast, isolated sand bodies formed in a lower-energy meandering system exhibit reduced connectivity and lower reservoir potential. Key controls were the interplay of tectonic activity and sea-level fluctuations that influenced the sediment distribution, channel migration, and stratigraphic architecture of this complex fluvial reservoir. The syn-rift Late Jurassic to Early Cretaceous clastic reservoir rocks of the West Netherlands Basin thus serve as a showcase example for subsurface fluvial reservoirs deposited in rift basins worldwide, emphasising the critical influence of tectonic and climatic factors on the distribution of reservoir heterogeneities and providing essential insights to identify sweet spots for successful geothermal exploration.

1. Introduction

Fluvial sandstones hold great potential for long-term geothermal exploration and CO₂ storage. Their excellent petrophysical and mechanical properties, such as high porosity and permeability, rank them among the best subsurface reservoirs and aquifers worldwide (Shanley, 2004). Yet, vertical and lateral variations in the distribution of porosity, a heterogeneous arrangement of permeable pathways, and the presence of impermeable barriers can pose significant challenges during reservoir characterisation (e.g., Miall, 1988). Additionally, types and dimensions of fluvial systems can vary significantly, affecting the reservoir quality at different scales (Hossain et al., 2023); i.e., sandstone-prone river compartments, such as point bars and channel belts, exhibit different production characteristics compared to shale-prone intervals, like

floodplain deposits. It is therefore crucial to determine the characteristics of the fluvial architecture in seismic data, such as the 3D geometry, orientation, spatial distribution, and total volume of the sand bodies (Potter, 1967; Allen, 1979; Allen et al., 1983; Hornung and Aigner, 1999; Bridge, 2001; Raiber et al., 2012), to effectively deploy them as reservoirs.

A good example of a basin with low-enthalpy geothermal reservoirs hosted in fluvial sandstones is provided by the West Netherlands Basin (WNB, Fig. 1). Here, the Late Jurassic to Early Cretaceous fluvio-deltaic syn-rift deposits of the Nieuwerkerk Formation are composed of three members, from base to top: the fluvial Alblaserdam and Delft Sandstone reservoir members, overlain by the sealing Rodenrijs Claystone Member (van Adrichem Boogaert and Kouwe, 1993; Fig. 2). These syn-rift sediments are part of a prolific and well-documented hydrocarbon system, as

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evidenced by numerous studies (e.g., de Jager et al., 1996; Herngreen et al., 2003; Willems et al., 2020). With the majority of the hydrocarbon fields being abandoned or on their final phase of production, interest shifted to geothermal energy, with the Delft Sandstone Member becoming the main geothermal target in the area (Mijnlieff, 2020; Willems et al., 2020; Buijze et al., 2023). The transition from hydrocarbon to geothermal exploration brought a shift in focus from the structural highs, traditionally targeted in hydrocarbon exploration, to the structural lows, which serve as favourable reservoirs for low-enthalpy geothermal energy systems. Consequently, structural and stratigraphic frameworks used to evaluate prospective areas had to be reconsidered to align with the new exploration objectives. The sand- and claystones of the Nieuwerkerk Formation result from a dynamic depositional history that is intertwined with the structural evolution of the basin, with fluvial systems being active during the final phase of rifting in the Late Jurassic (e.g., van Wijhe, 1987; den Hartog Jager, 1996; DeVault and Jeremiah, 2002; Weert et al., 2024). Consequently, the creation of accommodation space was strongly controlled by faults, which deeply influenced the architecture and evolution of the river system (cf. Gawthorpe and Leeder, 2000; Dillinger and George, 2019). As a result, the complex distribution of the sandy facies causes lateral and vertical variations in porosity, permeability, and net-to-gross ratios over short distances.

The hydrocarbon industry has provided a wealth of open-access seismic- and well data from the WNB, making the Nieuwerkerk Formation relatively well-studied (den Hartog Jager, 1996; DeVault and

Jeremiah, 2002; Willems et al., 2017; Vondrak et al., 2018; Willems et al., 2020). While the general depositional dynamics are well defined, key uncertainties remain in the details that are essential for de-risking and optimising geothermal exploration. A first key uncertainty is the fluvial dynamics that controlled the deposition of the Delft Sandstone and Alblasserdam members (Willems et al., 2017, 2020; Vondrak et al., 2018). In particular, the effects of tectonic activity and climatic fluctuations on the sediment supply and river channel migration. Secondly, the architecture of the fluvial systems is yet to be fully characterised, with the Alblasserdam Member remaining overlooked and under-explored (DeVault and Jeremiah, 2002; Willems et al., 2020). This is due to the lateral thickness variations, poorly understood architecture of the sandstones, and limited well control in the structural lows (DeVault and Jeremiah, 2002; Willems et al., 2017, 2020; Vondrak et al., 2018). As such, the potential for high-quality fluvial reservoir layers beneath the Delft Sandstone Member remains largely open. Furthermore, the connectivity between fluvial sandstone bodies, and thus the configuration of impermeable barriers, is still not fully understood (Vondrak et al., 2018; Willems et al., 2020). This information is critical for predicting fluid flow and optimising well placement during exploration and production phases.

This study integrates an extensive 3D seismic dataset, well log correlations, seismic attributes, and available biostratigraphic data to refine the knowledge of the seismic sedimentology of the Nieuwerkerk Formation. These insights are essential for improving reservoir characterisation and optimising geothermal exploration. Research on subsurface

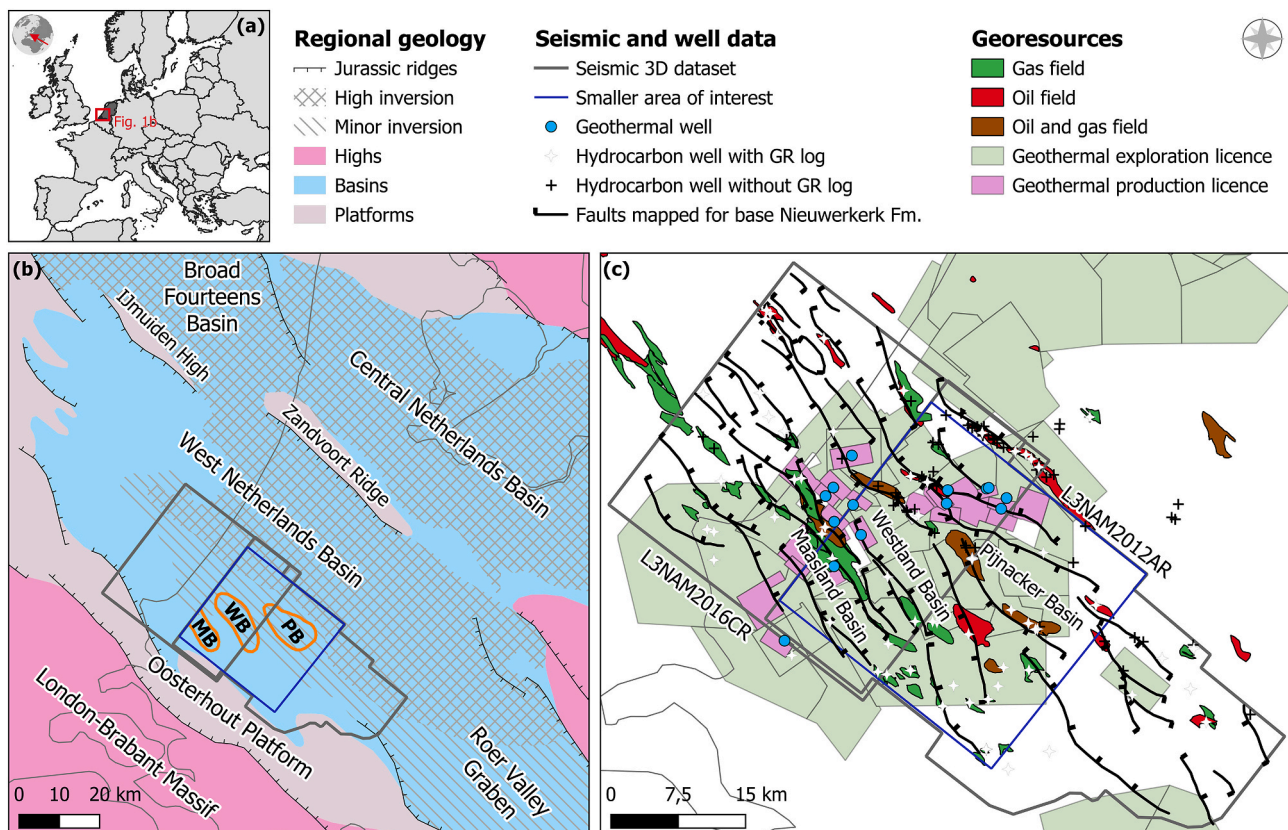


Fig. 1. (a) Location of the West Netherlands Basin (WNB) on the European continent, marked in red. (b) Map of the area around the WNB, showing the main structural elements during Jurassic times with the areas affected by the subsequent Late Cretaceous and Cenozoic inversion marked. The 3D seismic reflection datasets are displayed in grey. Highlighted in dark blue is the smaller area of interest, with the three selected sub-basins marked in orange. Sub-basin MB is part of the Maasland Basin, sub-basin WB is part of the Westland Basin, and sub-basin PB is part of the Pijnacker Basin (Weert et al., 2024). The regional geological elements on this map were produced by combining the maps from Wong et al. (2007) and Kombrink et al. (2012), and are published in Weert et al. (2024, 2025). (c) Map of the study area, with an overview of the current geothermal projects and present hydrocarbon fields, and mapped faults for the base of the Nieuwerkerk Formation published in Weert et al. (2025), together with the used well and seismic data. This map is modified from <https://www.nlog.nl/en/files-interactive-map> (last access: 9 October 2024). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

fluvial systems worldwide, particularly at burial depths greater than 2 km, has been limited, as most studies focus on shallower sequences (up to 2 km burial depth) where seismic resolution is typically better (e.g., Reijenstein et al., 2011; Van Heteren et al., 2014; Takano and Tsuji, 2017; Hossain, 2020; Al-Masgari et al., 2021; Wang et al., 2021; Zeng et al., 2022). The results of this study will not only enhance geothermal exploitation in the WNB, but also provide broader insights applicable to subsurface fluvial sandstone reservoirs worldwide.

2. Tectono-stratigraphic framework

The Nieuwerkerk Formation, which is the focus of this research, was deposited in the WNB and on the adjacent Oosterhout Platform (Fig. 1b), during the Late Jurassic to Early Cretaceous period (van Adrichem Boogaert and Kouwe, 1993; Duin et al., 2006; Kombrink et al., 2012; Verreussel et al., 2025; Fig. 2). The WNB and Oosterhout Platform developed upon a former Paleozoic basin, realigning with its NW-SE structural trend (e.g., Ziegler, 1992; van Balen et al., 2000; Worum et al., 2005). Multiple phases of Mesozoic extension, driven by the opening of the North Atlantic Ocean, led to the formation of the WNB, with the last phase of rifting occurring synchronous with the deposition of the Nieuwerkerk Formation (e.g., van Wijhe, 1987; van Balen et al., 2000; Willems et al., 2020; Weert et al., 2024). The basin entered a post-rift sag phase by the Early Cretaceous, during which the overlying marine Vlieland subgroup was deposited (Fig. 2). The African-European convergence induced compressional tectonics during the Late Cretaceous period (Kley and Voigt, 2008), causing positive inversion and inversion-related buttressing towards the NE of the WNB, reactivating pre-existing faults. Consequently, the Mesozoic sediments became uplifted, a process that continued into the Miocene (de Jager, 2003; Worum and Michon, 2005).

The Nieuwerkerk Formation is characterised by alternating non-marine sandstones and variegated claystones, the occurrence of isolated and stacked channelised sandstone bodies, coal beds, and paleosols (van Adrichem Boogaert and Kouwe, 1993; den Hartog Jager, 1996; Donselaar et al., 2015; Willems et al., 2017). These deposits exhibit a progressive southward shift over time, accompanied by an upward transition from primary red beds to coal-bearing grey beds. This

stratigraphic evolution reflects a changing climate from semi-arid to more humid conditions (den Hartog Jager, 1996; DeVault and Jeremiah, 2002; Willems et al., 2020). Extensional tectonics during deposition resulted in significant lateral variability in stratigraphic thickness and sedimentary facies (den Hartog Jager, 1996; Racero-Baena and Drake, 1996; DeVault and Jeremiah, 2002; Jeremiah et al., 2010). Additional rise and fall in relative sea level are assumed to have had an important effect on the formations' depositional pattern, yet whether this was due to eustasy or tectonics (or a combination thereof) remains speculative (den Hartog Jager, 1996).

The Nieuwerkerk Formation is subdivided into three lithostratigraphic members: the Alblasserdam Member at its base, followed by the Delft Sandstone Member, and capped by the Rodenrijs Claystone Member (van Adrichem Boogaert and Kouwe, 1993; Fig. 2). Yet, the Nieuwerkerk Formation also has other subdivisions: den Hartog Jager (1996) interpreted three fluvial-dominated sequences at the bottom, followed by one coastal-plane-dominated and one shallow marine sequence on top; DeVault and Jeremiah (2002) and Jeremiah et al. (2010) did not recognise the Delft Sandstone Member, arguing that sandstone bodies occur throughout the entire Nieuwerkerk Formation. With more recent studies recognising the Delft Sandstone Member (Donselaar et al., 2015; Willems et al., 2017, 2020; Vondrak et al., 2018; Verreussel et al., 2025), we use the original lithostratigraphic division by van Adrichem Boogaert and Kouwe (1993).

2.1. Alblasserdam Member

The Alblasserdam Member is the basal unit of the Nieuwerkerk Formation. It is characterised by alluvial plain deposits with single and stacked channel sandstones and overbank fines (den Hartog Jager, 1996; DeVault and Jeremiah, 2002; Willems et al., 2020; Verreussel et al., 2025). Its age is uncertain due to the absence of age-diagnostic microfossils and palynomorphs, but based on a stratigraphic correlation, it is assumed to have been deposited from the Late Kimmeridgian to Valanginian, ~150–137 Ma (van Amerom et al., 1976; den Hartog Jager, 1996; DeVault and Jeremiah, 2002; Willems et al., 2017; Vondrak et al., 2018; Verreussel et al., 2025; Fig. 2). Unconformably overlying the marine Altena Group, the Alblasserdam Member marks a shift to a

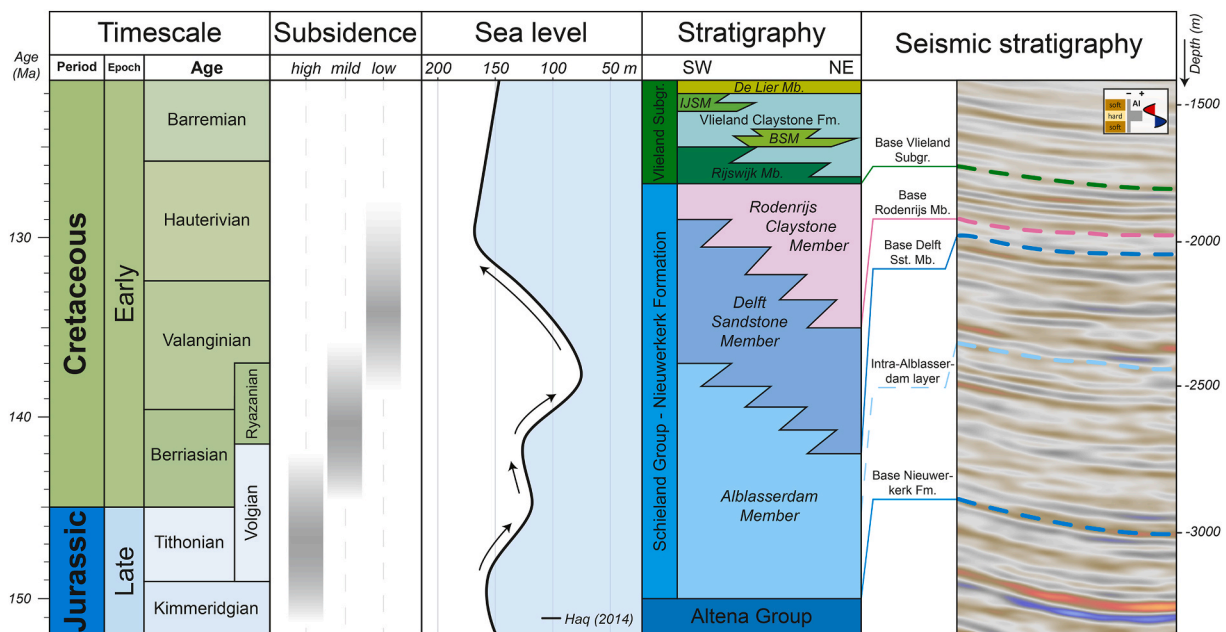


Fig. 2. The stratigraphic column of the Late Jurassic to Early Cretaceous as described in the stratigraphic framework, with abbreviations for the IJsselmonde Sandstone Member (IJSM) and Berkel Sandstone Member (BSM), seismic stratigraphy of the Nieuwerkerk Formation, long-term eustatic sea level curve from Haq (2014), and qualitative subsidence rate of the WNB, all tied to the ICS international chronostratigraphic chart (Cohen et al., 2013, version 2023/09).

tectonically and eustatic controlled (see Fig. 2), fluvial-dominated continental environment (DeVault and Jeremiah, 2002; Vondrak et al., 2018; Willems et al., 2020; Weert et al., 2024). Extensional faulting shaped the stratigraphic architecture and controlled the available accommodation space, as testified by distinct thickness variations from less than 100 m on the structural highs to 1300 m in the axis of half-grabens (den Hartog Jager, 1996; Vondrak et al., 2018), although isostatic compensation due to sediment loading likely contributed significantly as well. The rivers, sourced from the SE (likely the London-Brabant Massif, see Fig. 1b), followed the NW-SE elongated basin axis towards the NW, wherefore a decrease in sandstone/shale ratios from the proximal (SE) to distal (NW) is described in the WNB (den Hartog Jager, 1996; Vondrak et al., 2018). The few wells that drilled the entire succession, combined with seismic data, show the presence of red beds stacked channel deposits at the base of the Alblasserdam Member (den Hartog Jager, 1996) and loosely stacked meandering-river sandstone bodies in the top sections (Willems et al., 2020). Despite its geothermal potential, currently hosting two producing projects, reservoir characterisation remains challenging.

2.2. Delft Sandstone Member

The overlying Delft Sandstone Member consists of light-grey, massive sandstones interbedded with claystones, siltstones, and coal layers, interpreted as meandering distributary channels and associated floodplain fines in a coastal-plain setting (den Hartog Jager, 1996; Donselaar et al., 2015; Willems et al., 2017; Vondrak et al., 2018; Willems et al., 2020; Verreussel et al., 2025). Occurring throughout the entire WNB, this member can reach thicknesses of up to 250 m and conformably overlies the Alblasserdam Member in most areas (den Hartog Jager, 1996; Donselaar et al., 2015; Vondrak et al., 2018; Verreussel et al., 2025), though local disconformities are present (Willems et al., 2020). Recent studies documented a tectonically induced diachronous deposition over a broad time range during the Valanginian (~142–134 Ma, Fig. 2), with depocenters shifting from the NE to the SW (Willems et al., 2017; Vondrak et al., 2018). Consequently, the deposits can serve as a correlative equivalent to both the underlying Alblasserdam and overlying Rodenrijs members (Verreussel et al., 2025). Being interpreted as the sandstone-prone part of the Nieuwerkerk Formation and having a favourable thickness, permeability, and lateral extent, it is the primary geothermal aquifer in the region and represents the main target for the majority of the geothermal projects (Mijnlieff, 2020; Willems et al., 2020).

2.3. Rodenrijs Claystone Member

The Rodenrijs Claystone Member is the top unit of the Nieuwerkerk Formation, conformably overlying the Delft Sandstone Member and functioning as regional caprock. Deposited during the Late Valanginian to Hauterivian (~135–127 Ma, Fig. 2), the member marks the transition from fluvial to marginal marine conditions in the WNB (den Hartog Jager, 1996; DeVault and Jeremiah, 2002; Willems et al., 2017; Vondrak et al., 2018; Willems et al., 2020) and at its top records the shift from syn-rift to post-rift deposition (Donselaar et al., 2015). It consists of grey mudstones alternating with thin layers of sandstone and coal and was deposited in a coastal-plain to lagoonal setting (den Hartog Jager, 1996; DeVault and Jeremiah, 2002; Vondrak et al., 2018; Willems et al., 2020; Verreussel et al., 2025). Continued sea level rise during the Hauterivian caused a landward shift of fluvial facies from the N towards the S (den Hartog Jager, 1996; DeVault and Jeremiah, 2002; Willems et al., 2020). As a result, the boundary with the underlying Delft Sandstone Member is diachronous (den Hartog Jager, 1996; Willems et al., 2017; Vondrak et al., 2018; Verreussel et al., 2025). This is exemplified by claystones and thin sandstone layers with a thickening-upward trend, possibly representing washover sand bars in a lagoonal setting (Vis et al., 2010), are found in the lower part of the member, transitioning into lagoonal

black claystone facies towards the top (Willems et al., 2020). The members' boundary with the overlying barrier sandstones and lagoonal claystones of the Vlieland Subgroup is conformable, with the lowermost, sandstone-prone Rijswijk Member having a diachronous nature as well (Fig. 2). This testifies to the gradual landward stepping of facies as the relative sea level rise continued (den Hartog Jager, 1996; Verreussel et al., 2025).

3. Data and methods

This study uses two 3D seismic reflection datasets, 282 wells, and biostratigraphic data (Fig. 1c), all freely accessible at <https://www.nlog.nl/datacenter/> (last access: 9 October 2024). The L3NAM2012AR and L3NAM2016CR 3D seismic cubes are Pre-Stack Depth-Migrated (PSDM), which means they are depth-converted. The seismic dataset covers a total of 2300 km² of subsurface data from the onshore and offshore WNB, extending to a depth of 6 km. Technical details and information about the reprocessing can be found in the public processing reports that accompany the 3D seismic datasets on nlog.nl.

The seismic analysis was done in Petrel 2020.3 and built upon the interpretation by Weert et al. (2024, 2025). From that interpretation, the mapped horizons for the bases of the Vlieland Subgroup and the Nieuwerkerk Formation were used. Additionally, the bases of the Delft Sandstone and Rodenrijs Claystone members and an intra-Alblasserdam reflector (Fig. 2) were mapped for a smaller area (marked in dark blue in Fig. 1b), as the diachronous nature of these sediments makes their horizons difficult to trace throughout the entire dataset. This smaller area was selected based on its onshore location, the well coverage, and the diversity in sub-basins with varying depths and sizes.

By integrating the seismic interpretation with the understanding of the regional geology, seismic facies analysis was performed for the seismic units defined by the interpreted horizons. Here, different seismic facies are identified based on their reflection geometry and amplitude characteristics (e.g., Xu and Haq, 2022 and references therein). Within the Nieuwerkerk Formation, seven seismic facies are recognised, here named A to G (Fig. 3), with each seismic facies characterised by its own seismic architectural elements. When including the seismic interpretation and well logs, it is possible to tie the facies to the stratigraphy of the Nieuwerkerk Formation (Figs. 4 and 5).

In order to gain a more detailed understanding of the sedimentary characteristics of the Nieuwerkerk Formation, a well log correlation was done in Petrel 2020.3. From the 282 wells, only 136 are accompanied by well logs suitable for correlations (Fig. 1c). From this extensive dataset, nine wells were selected that are located inside the three selected basins (see below) and contain the majority of the sedimentary succession of the Nieuwerkerk Formation. The wells were directly tied to the depth-converted 3D seismic dataset, using the available data from nlog.nl. Gamma Ray (GR) logs were used for rock characterisation, allowing us to differentiate between lithologies and observe their characteristics at the well-bore scale (Fig. 3). Biostratigraphic data is available for 32 of these wells, which is published by DeVault and Jeremiah (2002), Jeremiah et al. (2010), and Willems et al. (2017). Additional biostratigraphic data can be found in technical reports by PanTerra Geoconsultants B.V., the NAM, and TNO, which are listed in the Data repository.

Sedimentological features are effectively characterised using seismic amplitude attributes, providing insights into the sediment distribution and lithological changes (Brown, 2001). To get a more detailed understanding of the sandstone distribution of the Delft Sandstone and Alblasserdam members, three sub-basins were selected to perform seismic attribute analysis: the Maasland, Westland, and Pijnacker basins (areas MB, WB, and PB, marked orange in Fig. 1b, with a more detailed overview in Fig. 6). In order to gain comparable results with similar amplitude properties, all areas are covered by the L3NAM2012AR 3D seismic dataset. The three selected basins have slightly varying characteristics in terms of depth and structural architecture (Figs. 4 and 6).

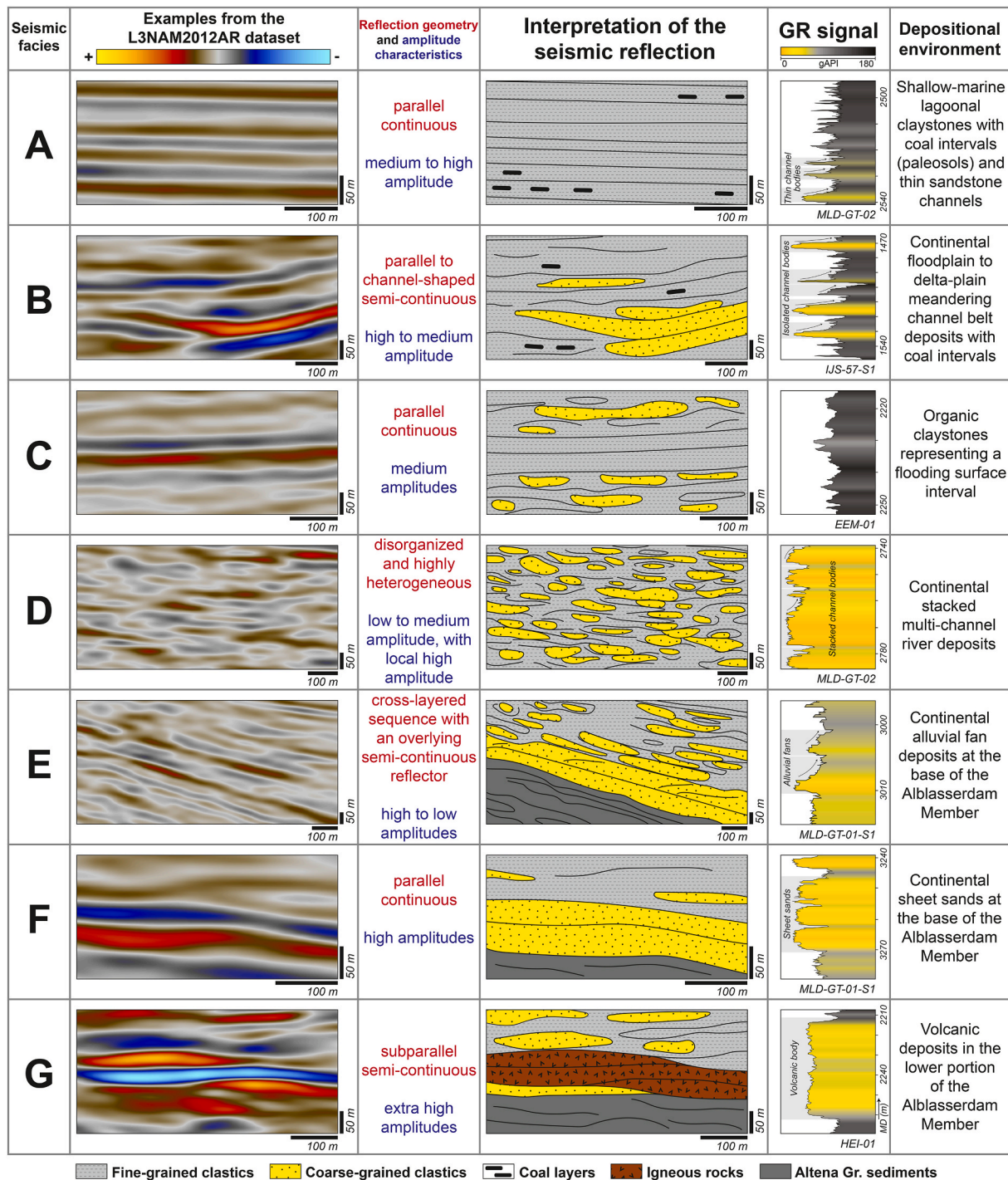


Fig. 3. Seismic facies library, illustrating the seven seismic facies recognised for the Nieuwerkerk Formation, identified from 3D seismic reflection data. For each facies, an example from the L3NAM2012AR seismic cube is shown, together with a description of the seismic features, the GR log signal, and the lithological interpretation, as described in the discussion section.

The Maasland Basin is an elongated graben structure (Fig. 1c). This basin is the shallowest, with the Nieuwerkerk Formation reaching thicknesses between 150 and 550 m. The Westland and Pijnacker basins are, in a first approximation, half-graben structures, with the Nieuwerkerk Formation reaching thicknesses between 600 and 1000 m for the Westland Basin and between 600 and 1400 m for the Pijnacker Basin.

For all three basins, amplitude maps were generated using the Root-Mean-Square (RMS) amplitude extraction technique. This is used to quantify the square root of the average of the squares of a series of amplitudes of reflected seismic waves within a specified time or depth

window, typically corresponding to a seismic horizon or layer of interest (e.g., Brown, 2011). Within this horizon or layer, RMS amplitude is calculated for each seismic trace along the line or across the 3D seismic volume. The resulting RMS values are then mapped spatially across a horizon or time slice surface to create amplitude maps. RMS amplitude highlights areas of high energy, which are often associated with strong contrasts in acoustic impedance, such as those found in fluid-filled reservoirs or lithological changes, thus revealing changes in sediment distribution. In this study, amplitude extraction is applied to two intervals of the Nieuwerkerk Formation: in between the base of the Rodenrijs

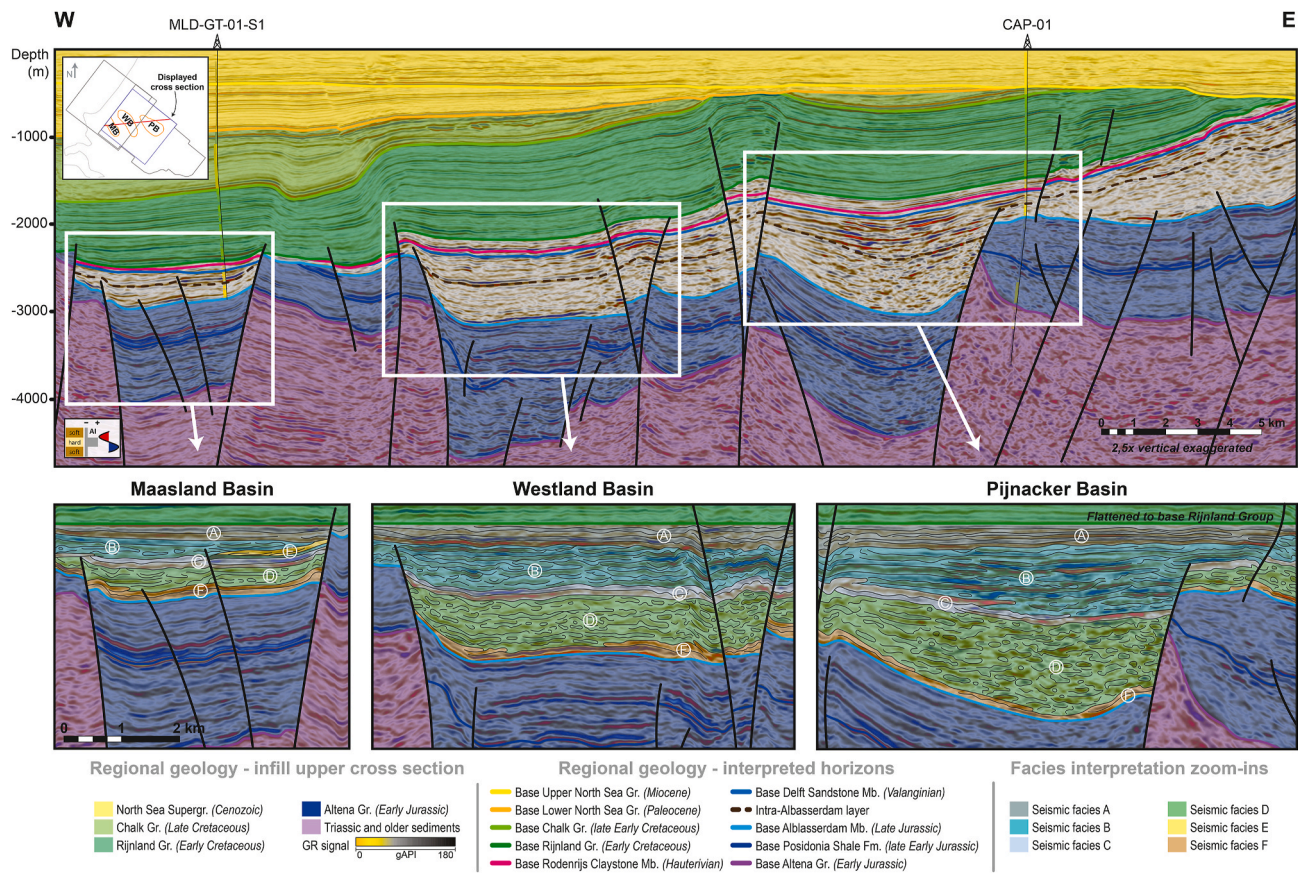


Fig. 4. A 1:2,5 scaled seismic cross-section, location in the dataset marked red in the map in the upper left corner, showing the main faults, main interpreted horizons, the GR logs of the two wells the lines crosses, and sedimentary packages. The zoom-ins on the Maasland, Westland, and Pijnacker basins show seismic cross-sections flattened for the top of the Nieuwerkerk Formation, with interpreted seismic facies A to F. Seismic facies G is absent, as the igneous rocks are only recognised on a few locations throughout the WNB. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Member and the intra-Alblasserdam layer, and between the intra-Alblasserdam layer and the base of the Alblasserdam Member.

4. Results

4.1. Seismic facies

Seven seismic facies can be recognised for the Nieuwerkerk Formation (facies A to G, Fig. 3), all showing distinct characteristics of reflectors and geometries. The majority of the facies appear at a specific stratigraphic height within the Nieuwerkerk Formation, here described from top to bottom.

4.1.1. Seismic facies A

Seismic facies A is identified in the upper portion of the Nieuwerkerk Formation, reaching thicknesses up to 200 m (Fig. 4). This facies is characterised by parallel, continuous reflectors with medium-to high-amplitudes (Fig. 3). In seismic cross-sections, facies A can be well traced for long distances, sealing the underlying basin fill. It is directly overlain by the Vlieland Subgroup and corresponds to the Rodenrijs Claystone Member.

4.1.2. Seismic facies B

Seismic facies B appears in the upper part of the Nieuwerkerk Formation (Fig. 4) and has a variable thickness, attaining values of up to 500 m in the deepest parts of the sub-basins. It is characterised by parallel to channel-shaped, semi-continuous reflectors that have high-to medium-amplitudes, that can have thicknesses between 20 and 100 m (Fig. 3). Facies B is observed at the stratigraphic height of the Delft

Sandstone Member and the upper half of the Alblasserdam Member. In seismic cross-sections, the high-amplitude zones are predominantly concentrated in the central parts of the half-grabens and are more prevalent at the stratigraphic level of the Delft Sandstone Member. Medium-amplitude zones, on the other hand, tend to appear away from the central basin parts, appearing near the basin-bounding faults (Fig. 4).

4.1.3. Seismic facies C

Seismic facies C is characterised by parallel, continuous reflectors with medium amplitudes (Fig. 3). Facies C bears similarities to seismic facies A, but with distinctive differences: facies C is significantly thinner (up to 90 m) and occurs lower in the stratigraphy, restricted to the Alblasserdam Member, where it forms a boundary between facies B above and facies D below. In the majority of the study area, facies C is expressed as a package of two, occasionally three, consistent seismic reflectors. Its impedance contrast and amplitude strength vary, depending on the composition of the surrounding rocks. Although thin, seismic facies C forms a laterally persistent reflector package that can be traced across the entire study area (Fig. 4), suggesting that it may represent a regionally correlatable seismic marker within the seismic succession of the Nieuwerkerk Formation.

4.1.4. Seismic facies D

Seismic facies D is defined by disorganised and highly heterogeneous reflectors that comprise low-to medium-amplitudes, with some local high-amplitude zones (Fig. 3). It is generally overlain by seismic facies C and appears in the lower half of the Alblasserdam Member. Here, facies D shows variable thicknesses, reaching up to 800 m in the lowest parts of

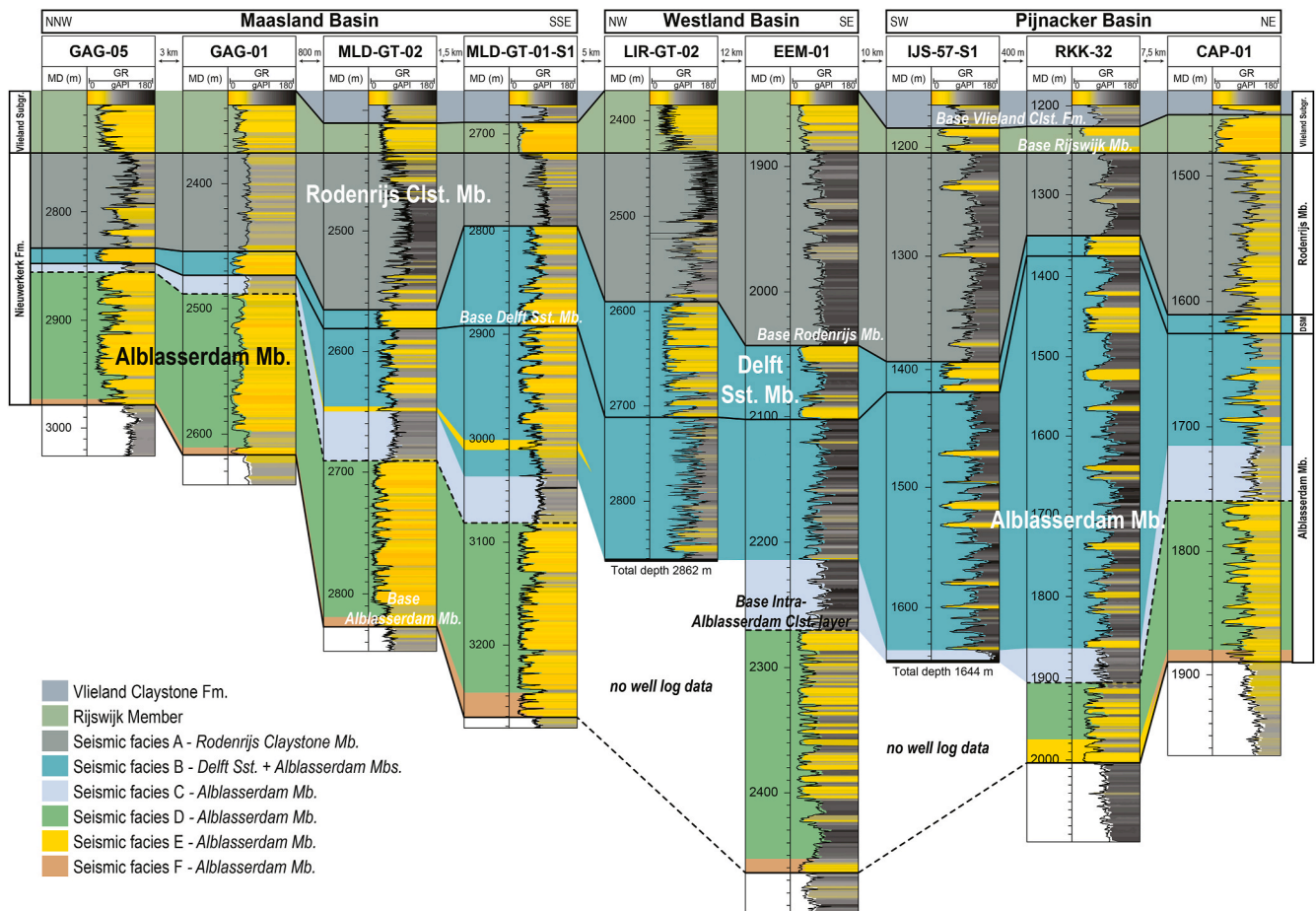


Fig. 5. Correlation panel through the Maasland, Westland and Pijnacker basins (see Fig. 6 for well locations). The well deviation has no significant effect on the thickness of the stratigraphic packages, wherefore only the measured depth (MD) is projected. Wells LIR-GT-02 and IJS-57-S1 only include the sedimentary sequence up into the upper part of the Alblasterdam Member. The panel displays the correlation of the lithostratigraphic units of the Nieuwerkerk Formation and seismic facies A to F. The bases of the lithostratigraphic units are indicated with thick black lines, and the intra-Alblasterdam Claystone layer by a dotted black line. The colours represent the seismic facies. Note the appearance of seismic facies F in the basal part of the Alblasterdam Member, the potential presence of seismic facies E in the MLD-GT and RKK-32 wells, and the continuous presence of the intra-Alblasterdam Claystone layer, represented by seismic facies D. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the sub-basins, filling the majority of the lower half of the half-grabens (Fig. 4).

4.1.5. Seismic facies E

Seismic facies E is characterised by inclined sequences that have a semi-continuous reflector on top (Fig. 3). Generally, the inclined sequences display low-to medium-amplitudes, with the overlying semi-continuous reflector having a medium-to high-amplitude. Facies E has a varying thickness, generally between 10 and 90 m (Figs. 3 and 5). It is typically found near basin-forming faults, being identified throughout the entire stratigraphic sequence of the Alblasterdam Member (Figs. 4 and 5).

4.1.6. Seismic facies F

Seismic facies F comprises parallel-layered, continuous reflectors with high amplitudes (Fig. 3). This facies can reach thicknesses of up to 90 m and is primarily found at the bottom of the Alblasterdam Member, where it is generally overlain by seismic facies D and underlain by the sediments of the Altena Group (Fig. 4).

4.1.7. Seismic facies G

Seismic facies G appears very local, featuring subparallel, semi-continuous reflectors with very high amplitudes (Fig. 3). Within the WNB, igneous rocks in the Nieuwerkerk interval have been encountered

in offshore wells P09-08 and P12-08, and onshore wells GSD-01 and HEI-01. Therefore, seismic facies G can be linked to igneous rocks identified in well data, which typically appear in the basal part of the Alblasterdam Member.

4.2. Well log correlation

Well log correlation complements the characterisation of the seismic sedimentology, allowing for a description of the lithologies that make up the seismic facies (Fig. 3). The nine wells included in the well log correlation comprise four wells on the NE flank of the Maasland Basin (GAG-05, GAG-01, MLD-GT-02, MLD-GT-01-S1), two wells on the SW flank of the Westland Basin (LIR-GT-02, EEM-01), two wells on the SW flank of the Pijnacker Basin (IJS-57-S1, RKK-32), and one well on the NE flank of the Pijnacker Basin (CAP-01, Figs. 5 and 6). All wells, except for LIR-GT-02 and IJS-57-S1, encountered the full succession of the Nieuwerkerk Formation.

Seismic facies A can be tied to the Rodenrijs Claystone Member and is composed of claystones that are interbedded with thin layers of sandstones. The majority of these sandstone intervals show a fining upward trend with a sharp base on the GR logs (Fig. 3). Directly below, seismic facies B displays alternating intervals of finer-grained claystones and coarser-grained sandstones (Figs. 3 and 5). Typically, a higher portion of sandstone deposits is present at the stratigraphic level of the Delft

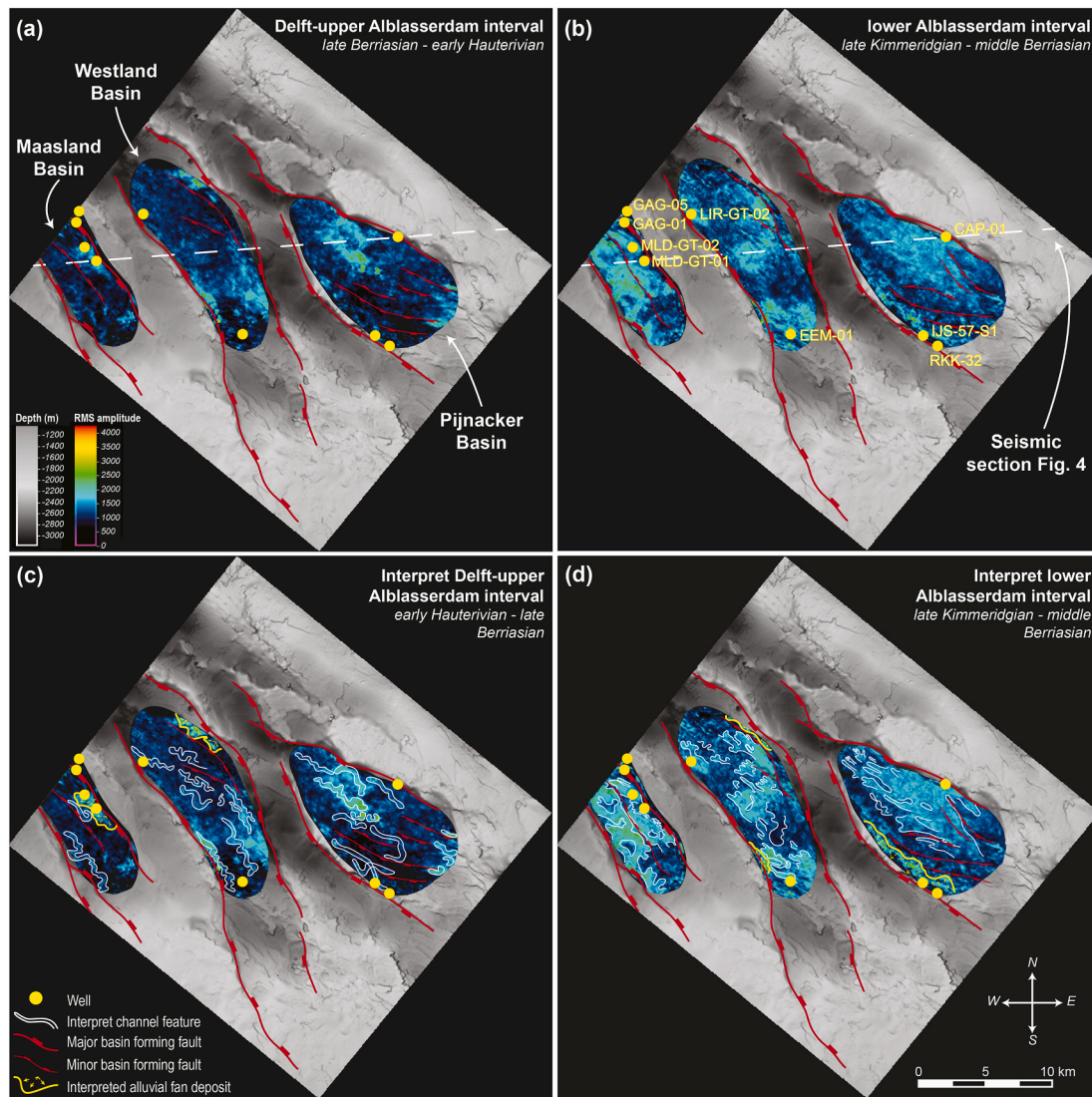


Fig. 6. RMS amplitude maps for the Delft-upper Alblasterdam and lower Alblasterdam intervals, together with the wells presented in Fig. 5. The Delft-upper Alblasterdam interval includes the material in between the horizons of the base Rodenrijs Claystone Member and intra-Alblasterdam Claystone layer. The lower Alblasterdam interval is composed of the material in between the horizons of the intra-Alblasterdam Claystone layer and base Nieuwerkerk Formation (see Fig. 2 for the horizons). The RMS amplitude extraction is projected non-transparently on a depth map of the base Nieuwerkerk Formation horizon. Figures a and c show the non-interpret RMS amplitude extraction, and figures b and d show the interpretation for both intervals.

Sandstone Member, which correlates to the increased amount of high-amplitude reflectors that is observed at this depth. The sandstone layers for the interval of the Delft Sandstone Member show both fining-upward and cylindrical trends. In contrast, facies B generally displays a sawtooth trend for the upper portion of the Alblasterdam Member (Fig. 5). Here, a higher portion of claystones alternates with sandstone intervals. For wells GAG-05 and GAG-01, seismic facies B is only observed at the stratigraphic level of the Delft Sandstone Member, being absent for the Alblasterdam Member.

Below, seismic facies C is composed of claystone deposits (Figs. 3 and 5). It separates the overlying seismic facies B from the underlying seismic facies D. Facies D shows a sandstone-prone sequence, composed of stacked coarse-grained sandstones with thin intervals of claystones (Fig. 3). The majority of the sandstone packages are regular with sharp tops and bases, also known as a cylindrical GR trend. At the bottom of the Alblasterdam Member, a sandstone-prone package with a blocky trend can be observed, which corresponds to the continuous high-amplitude reflectors of seismic facies F (Fig. 3).

On seismic cross-sections, seismic facies E can be identified throughout the Alblasterdam Member. When correlated with GR logs,

facies E is distinguished by a fining-upward trend with a coarse-grained basal layer (Fig. 3). Here, it is observed in both the upper portion of the Alblasterdam Member (wells MLD-GT-02 and MLD-GT-01-S1) and in the lower portion of the Alblasterdam Member (well RKK-32). The volcanic deposits of seismic facies G, which is not featured in the well log correlation of Fig. 5, are characterised by a cylindrical GR appearance (Fig. 3).

4.3. Seismic facies distribution

RMS amplitude extraction further complements the seismic facies characterisation. It was conducted for two intervals in the Maasland, Westland, and Pijnacker basins: the Delft-upper Alblasterdam interval and the lower Alblasterdam interval. The Delft-upper Alblasterdam interval includes the material in between the horizons of the base Rodenrijs Claystone Member and intra-Alblasterdam Claystone layer. The lower Alblasterdam interval is composed of the material in between the horizons of the intra-Alblasterdam Claystone layer and base Nieuwerkerk Formation (see Fig. 2 for the horizons). The Delft-upper Alblasterdam interval is primarily composed of seismic facies B,

whereas the lower Alblasserdam interval mainly contains seismic facies D (Figs. 4 and 5). The amplitude maps are projected on a depth map for the base Nieuwerkerk Formation, showing the facies distribution relative to the Late Jurassic basin architecture (Fig. 6). When compared with the GR logs (see Figs. 3 and 5), high-amplitude areas (>1500) can be interpreted as sandstone-prone, while low-amplitude areas (<1500) are taken as indicative for shale-prone deposits.

The RMS amplitude map for the Delft-upper Alblasserdam interval reveals both sandstone-prone and shale-prone regions (Fig. 6a). The sandstone-prone regions are best resembling features related to meander channel deposits (Fig. 6c). In the Pijnacker Basin, oxbow lake geometries are recognised as well. These meandering river deposits typically appear in the central parts of the half-grabens, where they follow the NW-SE elongated basin axis. Sandstone-prone deposits with extra high amplitudes (>2500) are recognised as well and can be correlated to seismic facies E. These areas are located adjacent to major basin-forming faults on the margins of the Maasland and Westland basins and are here interpreted as alluvial fan deposits. In the Maasland Basin, the observed extra high amplitude region is also identified in the MLD-GT wells (seismic facies E in Fig. 5).

Compared to the Delft-upper Alblasserdam interval, the lower Alblasserdam interval displays a greater proportion of sandstone-prone regions (Fig. 6a versus Fig. 6b), which correlates to the stacked sandstone deposits interpreted from the well log observations (Fig. 5). Although the image (Fig. 6b) is open to more than one interpretation, this study interprets the sandstone-prone regions in the lower Alblasserdam interval as a multi-channel fluvial system (e.g., Wang et al., 2021; Fig. 6d); other interpretations are considered in the Discussion. The sandstone-prone deposits are located in the central, deeper sections of the half-grabens, where the sandstone-prone deposits with extra high amplitudes (>2500) of seismic facies E are also present. Located in the Westland and Pijnacker basins, they appear along the half-graben margins, adjacent to major basin-forming faults.

5. Discussion

5.1. Interpretation of the seismic facies

Seven seismic facies are identified for the Nieuwerkerk Formation (seismic facies A to G, see Fig. 3) based on their seismic expression and gamma-ray log characteristics, and can be recognised at both the seismic and well-log scale. In detail, the Rodenrijs Claystone Member is composed of seismic facies A, the Delft Sandstone Member of seismic facies B, and seismic facies B to G are observed within the Alblasserdam Member.

5.1.1. Seismic facies A

Seismic facies A is composed of continuous reflectors that can reach thicknesses of up to 200 m and represent claystone deposits interbedded with thin layers of sandstones (Figs. 3–5). These deposits represent the Rodenrijs Claystone Member and can be associated with tidal parasequences deposited in a retrograding system (Cant, 1992). The observed local high amplitudes are typical for organic matter accumulations or coal intervals, associated with the presence of paleosols within the Rodenrijs Claystone Member (den Hartog Jager, 1996; DeVault and Jeremiah, 2002; Willems et al., 2020). The GR logs show a bell-shaped fining upward trend for the sandstone layers (Fig. 3), which is indicative for fluvial or tidal channel deposits (Cant, 1992). These channel deposits typically appear in the lower portion of the Rodenrijs Member (Fig. 5).

5.1.2. Seismic facies B

Seismic facies B is composed of alternating sandstone and claystone intervals (Figs. 3 and 5) and is expressed on seismic cross-sections by parallel to semi-continuous, channel-shaped reflectors with medium-to high-amplitudes (Figs. 3 and 4). The facies has a variable thickness, reaching up to 500 m in the deepest parts of the sub-basins, reflecting

syn-depositional tectonic activity. Individual channel bodies within seismic facies B typically range from 20 to 100 m in thickness, indicating the presence of thinner isolated channel fills and thicker bodies forming vertically stacked channel intervals.

High-amplitude regions with sandstone-prone channel features are more common in the Delft Sandstone Member compared to the upper portion of the Alblasserdam Member, correlating with the overall coarsening upwards in the GR logs that can be observed for seismic facies B (Fig. 5). The semi-continuous high-amplitude reflectors that are present can be interpreted as amalgamated channel features (e.g., Schwab et al., 2007; Lowe et al., 2019), where the combination of organic matter accumulations and sandstones in the channel belt, along with nearby levees and crevasse splays, produces the observed regions with strong impedance contrasts and high amplitudes. The interpreted sinuous channels and oxbow lake deposits on the RMS amplitude map (Fig. 6c) further aid the interpretation of a meandering river environment.

5.1.3. Seismic facies C

Seismic facies C is generally between 60 and 90 m thick and composed of parallel, continuous, medium-amplitude reflectors that likely resemble organic-rich claystones (Figs. 3–5). This appearance of facies C resembles a floodplain-dominated depositional environment, which has been documented for the Nieuwerkerk Formation (den Hartog Jager, 1996; DeVault and Jeremiah, 2002). Its basin-wide persistence suggests that facies C may represent a regionally extensive stratigraphic interval, making it a useful seismic marker within the succession.

5.1.4. Seismic facies D

Seismic facies D is characterised by disorganised and highly heterogeneous reflectors with low to medium amplitudes. It records syn-depositional tectonic activity, with a highly variable thickness that locally reaches up to 800 m in the deepest parts of the sub-basins. The disorganised pattern of seismic facies D on seismic cross sections is interpreted to result from the presence of laterally discontinuous and locally amalgamated sandstone bodies, indicating deposition in a high-energy setting.

On RMS amplitude maps (Fig. 6d), the sandstone-prone features form irregular, elongated geometries that may represent channel belts and associated bar forms. Such geometries are commonly associated with braided fluvial systems (e.g. Wang et al., 2021; Liu et al., 2021). However, similar seismic expressions may also arise from amalgamated channel complexes with associated crevasse splays in high-energy meandering systems (e.g. Lowe et al., 2019), where individual channel forms become difficult to distinguish. The blocky to cylindrical upward trends observed in the gamma-ray logs are likewise consistent with stacked channel fills (e.g., Cant, 1992; Wang et al., 2021), but are not uniquely diagnostic of stacked braided river fills.

The generally low to medium seismic amplitudes are attributed to the dominance of sandstone and the limited presence of organic matter accumulations, resulting in reduced impedance contrasts (den Hartog Jager, 1996). In addition, the relatively low seismic contrast of facies D, together with the resolution of the seismic dataset and possible tuning effects, may further obscure detailed channel geometries, introducing additional uncertainty in distinguishing between braided and meandering fluvial systems. Importantly, seismic facies D differs markedly from the overlying facies B in reflector organisation, amplitude character, and internal heterogeneity. The transition between the two facies is abrupt rather than gradual, which is difficult to reconcile with progressive effects such as compaction, diagenesis, or seismic processing. Instead, this sharp change in seismic character suggests a shift in depositional style, implying that facies D records a fluvial system distinct from that of facies B. Taken together, the seismic characteristics of facies D indicate deposition in a higher-energy, multi-channel fluvial system with an architecture that is fundamentally different from that of

facies B, although the precise fluvial style remains open to interpretation.

5.1.5. Seismic facies E

The low-amplitude, inclined reflector sequences that define seismic facies E (Fig. 3) are interpreted to reflect pronounced sediment heterogeneity, combined with the GR log signature, which shows a fining-upward trend with a coarse-grained basal layer (Figs. 3 and 5), these characteristics might indicate the presence of coalescent alluvial fan deposits (i.e. aprons) (e.g., Zhu et al., 2014), which display thicknesses between 10 and 90 m. This interpretation is further supported by the RMS amplitude maps (Fig. 6), where seismic facies E appears as zones with extra high amplitudes that are located adjacent to major basin-forming faults. This spatial association suggests a strong tectonic control on sediment delivery, consistent with syn-depositional fault activity driving localised sediment influx from uplifted areas. However, it should be noted that similar seismic expressions may also arise from other coarse-grained, proximal depositional environments, and that the limited seismic resolution may obscure detailed internal architectures. Consequently, while an alluvial fan interpretation is considered plausible for seismic facies E, alternative proximal fluvial or debris-dominated depositional scenarios cannot be entirely excluded.

5.1.6. Seismic facies F

The parallel, high-amplitude reflectors of seismic facies F can be correlated to a sandstone-prone package at the base of the Alblasserdam Member that can reach a thickness of 90 m. Its smooth, uniform appearance is characteristic of sheet sandstone bodies (Xu and Haq, 2022), with the high amplitudes resulting from the impedance contrast between coarse-grained sandstones of facies F, the fine-grained deposits of the underlying Altena Group, and the overlying river deposits of seismic facies D. Facies F likely resembles the continental sheet sandstones that are reported at the base of the Alblasserdam Member (den Hartog Jager, 1996; DeVault and Jeremiah, 2002).

5.1.7. Seismic facies G

Core data has shown that the semi-continuous, high-amplitude reflectors of seismic facies G (Fig. 3) represent volcanic deposits. These

igneous rocks are presumed to be part of the West Netherlands Igneous Province (Sissingh, 2004), which is associated with the rift-related tectonic activity in the basin. However, the intrusive or extrusive nature of these volcanic rocks remains uncertain, leaving their provenance unidentified.

5.2. River entry and exit points

By combining seismic, structural, and sedimentological data, an interpretation for the entry and exit points of the river systems active in the Maasland, Westland, and Pijnacker basins can be made (Fig. 7). While in single-phase rifting, isopach maps can help in understanding sediment routing (e.g., Zwaan, 2018), the occurrence of inheritance in the WNB requires incorporating the pre-rift geometry in the analysis. Comparing the depth map of the top Triassic (pre-rift for the second rifting event) and the base of the Nieuwerkerk Formation (second syn-rift) reveals areas that evolved into structural features that likely controlled the nucleation and evolution of entry and exit points of the river systems into the basins.

For the Maasland Basin, the top Triassic depth map shows the presence of an elongated graben, with two adjacent horsts (Fig. 7a). During the Late Jurassic, this graben evolved into a wider and shorter graben, the Maasland Basin (Fig. 7b). It is likely that the underlying Triassic-Jurassic graben structure functioned as a minor depression in the landscape, controlling the direction of the river system. The entry point for the river system that flowed through the Maasland Basin was therefore located in the SE, following the former NW-SE elongated basin axis.

The Westland Basin developed upon a former horst-and-graben structure as well. Here, the top Triassic depth map shows the presence of a relay ramp at the basin's NE border fault (Fig. 7a). The two fault segments did not fully connect during the Late Jurassic, wherefore this area remained slightly higher than the surrounding graben topography, forming a sloping corridor into the Westland Basin (Fig. 7b). This slope is interpreted to be a river entry point, which is supported by the presence of sandstone-prone channel deposits at the lower part of the slope (Figs. 6 and 7b).

For the Pijnacker Basin, a river exit point can be observed. The top

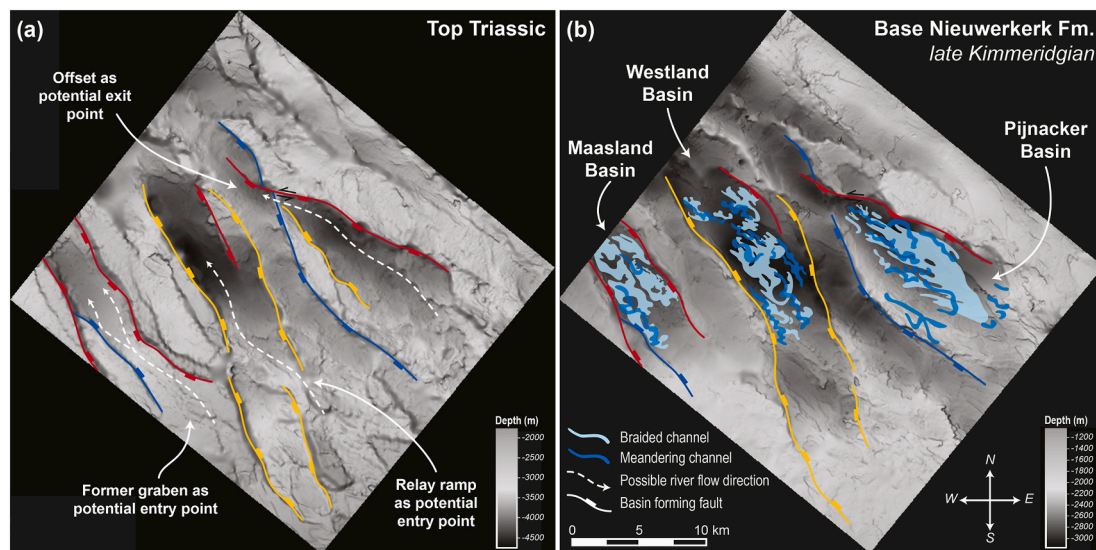


Fig. 7. Interpretation for the entry and exit points and flow directions of the Nieuwerkerk river system within the Maasland, Westland, and Pijnacker basins. The highlighted basin-forming faults have been given different colours to make them easily distinguishable from one another. Figure (a) shows the depth map of the top Triassic horizon with the important structural elements indicated. Those areas accommodate later entry and exit points of the Nieuwerkerk river system. Based on their location, an interpretation for the flow direction of the Nieuwerkerk river system was made. Figure (b) shows the depth map of the horizon of the base Nieuwerkerk Formation with the interpretation of the RMS amplitude extraction maps of Fig. 6c and d. Also here, the interpretation of the flow direction of the Nieuwerkerk river system is drawn. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Triassic depth map shows the basin's SW border fault (blue fault in Fig. 7a) being sinistrally offset by the NE border fault (red fault in Fig. 7a). During the Late Jurassic, the area where the SW fault intersects with the NW fault was not fully reactivated, forming a topographic depression. The RMS amplitude maps show that the sandstone-prone deposits seem to prograde towards this depression, wherefore it is interpreted to be the exit point of the river system.

Understanding how the underlying structural framework influences the depositional pattern of a syn-kinematic river system is essential when determining sandstone-prone zones in a heterogeneous fluvial reservoir. Buried structural features, such as half-grabens, relay ramps, and areas offset by strike-slip movement, can evolve into areas where a river system entered or exited the fault-bounded basin. Defining these zones supports the search for sandstone-prone zones in these types of reservoirs, which enhances well planning and helps de-risk geothermal projects.

5.3. Updated seismic sedimentology

This section gives an updated seismic-sedimentological description for the Nieuwerkerk Formation. Because of the clear distinction between seismic facies B and D, the description of the Alblasserdam Member is split into the lower Alblasserdam Member and the upper Alblasserdam Member. By integrating biostratigraphic data with observations from seismic reflection and well log data, the facies distribution can be defined and correlated with the spatial-temporal evolution of the interpreted depositional environments (Fig. 8). This way, the influence of both tectonics and sea-level fluctuations on the sediment deposition can be constrained. It should be noted that biostratigraphic data are only

available for the *forbesi*, *pingue*, *denckmanni*, *elegans*, *gottschei*, and *paratollia* boreal stages, and that no data are available for the lower section of the Alblasserdam Member.

5.3.1. Lower Alblasserdam Member

Sedimentation of the Nieuwerkerk Formation was driven by tectonic and climatic processes. The late Kimmeridgian eustatic highstand and subsequent starting of the Tithonian global sea-level drop marked the change from a marine to a continental depositional environment in the WNB (Fig. 2). Simultaneously, Late Jurassic rifting created a series of half-grabens that provided the necessary accommodation space and topographic relief for the high-energy, multi-channel river environment that deposited the sandstone-prone seismic facies D, E, and F, which make up the majority of the lower Alblasserdam Member (Figs. 3–5). Initially, accommodation space was likely limited, with deep half-grabens and steep margins, characterised by localised erosion and sediment bypass. This high-relief setting favoured an increased sediment supply, resulting in the sheet sands of seismic facies F at the bottom of the Alblasserdam Member, which is characterised by parallel-layered high-amplitude reflectors and a cylindrical GR-signal (Fig. 3). Active faulting induced sediment transport from elevated areas, producing the coalescing alluvial fans and aprons of seismic facies E along the half-graben margins (Fig. 9a). These deposits can be distinguished by inclined high to low amplitude reflectors and a fining-upwards bell-shaped GR signal (Figs. 3 and 5). The sediments were likely sourced from exposed Altena Group deposits on adjacent structural highs and, more locally, from Triassic strata exposed along the basins' SE margin. Enhanced tectonic activity in the lower Alblasserdam Member is further demonstrated by the presence of the volcanic rocks of seismic facies G in

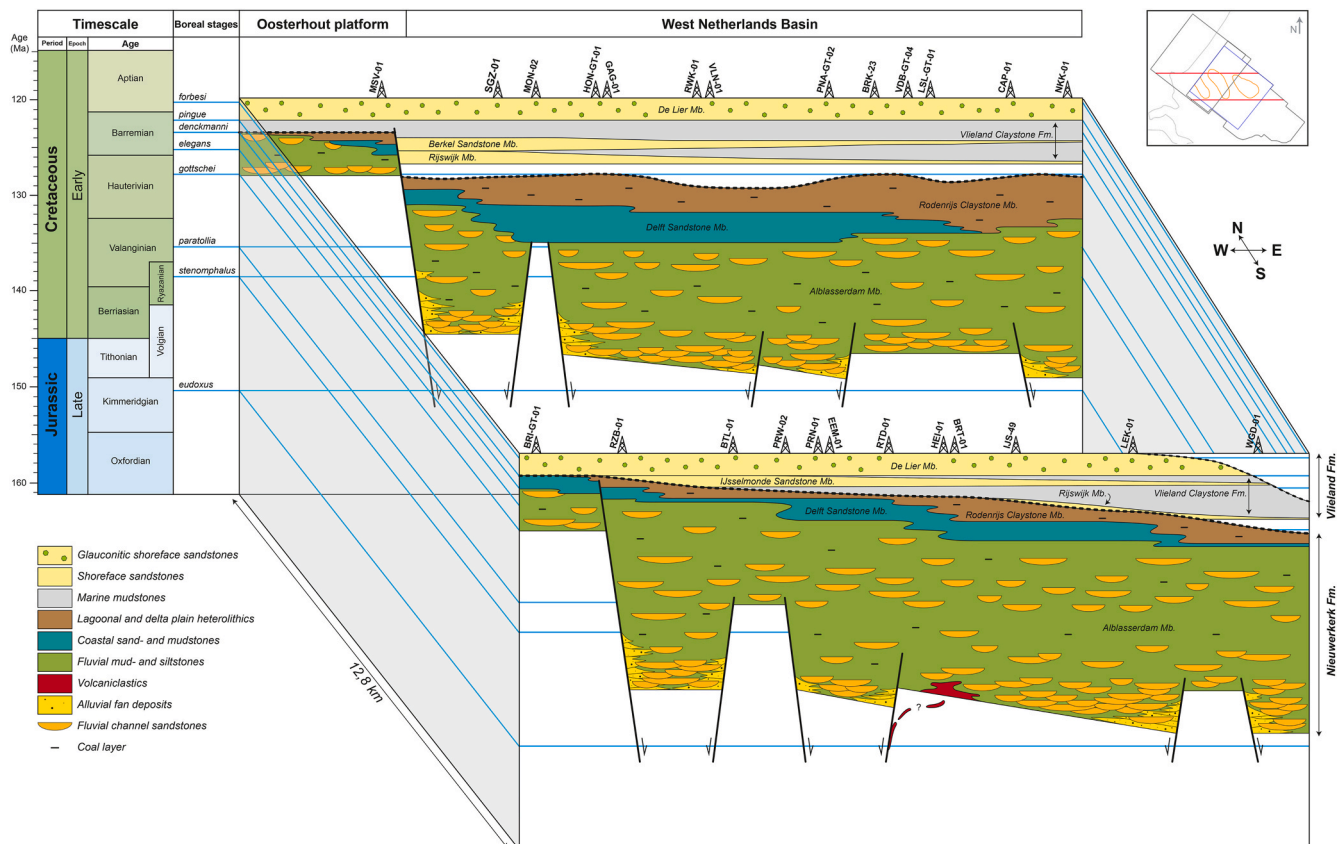


Fig. 8. Interpretation for the sedimentary distribution of the Nieuwerkerk Formation, tied to the ICS international chronostratigraphic chart (Cohen et al., 2013, version 2023/09). This figure is based on available biostratigraphic data from DeVault and Jeremiah (2002), Jeremiah et al. (2010), Munsterman (2012), Willems et al. (2017), and technical reports by PanTerra Geoconsultants B.V., the NAM, and TNO, which are listed in the Data Repository. There was no biostratigraphic data available for wells CAP-01, HEI-01, LEK-01, RZB-01, SGZ-01, and WGD-01. Apart from the Nieuwerkerk Formation, this figure also comprises the lower succession of the Vlieland Subgroup, as the deposition of its barrier sands coincides with the deposition of the Nieuwerkerk Formation on the Oosterhout Platform.

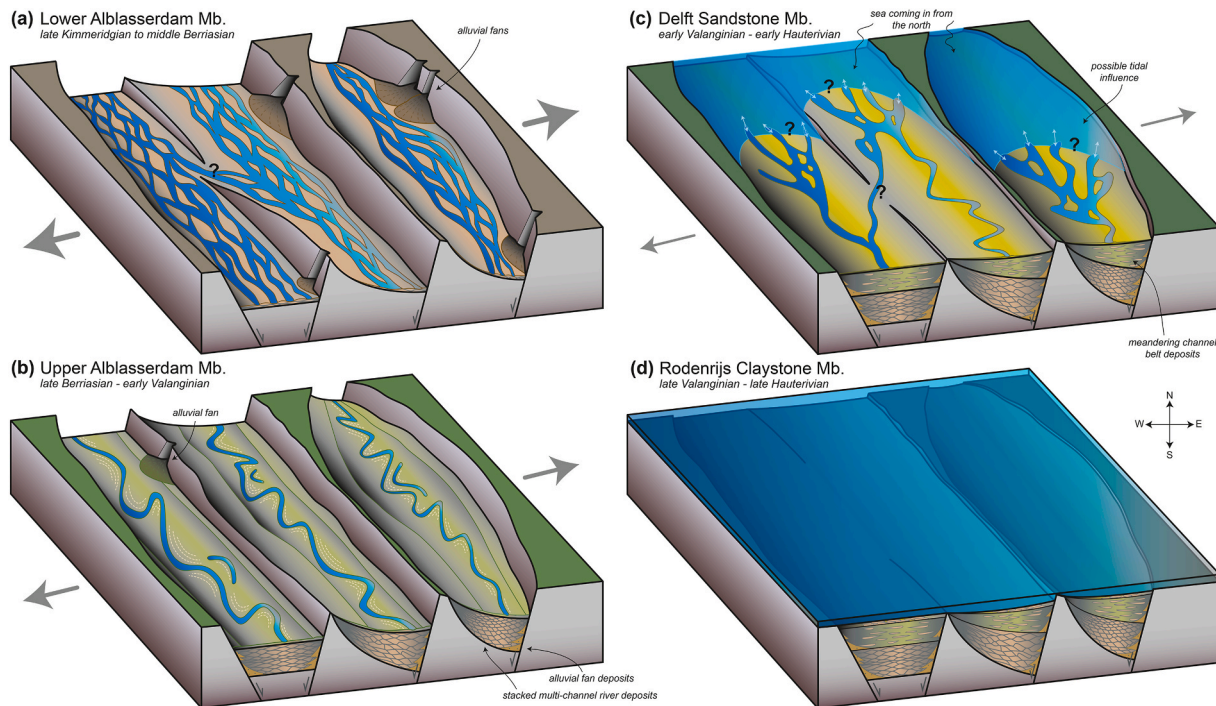


Fig. 9. Schematic figure showing the deposition of the reservoir rocks of the Nieuwerkerk Formation in the WNB over time; (a): deposition of the stacked sandstones of the lower Alblasserdam Member during the Late Jurassic rifting phase, (b): deposition of the isolated meandering channels of the upper Alblasserdam while rifting was less strong but still continuing, (c): deposition of the delta-plain sandstones of the Delft Sandstone Member while rifting was halting and the sea level was rising, and (d): deposition of the marine claystones of the Rodenrijs Claystone Member.

the basal part of the member.

As both rifting and sedimentation continued, the half-grabens were progressively filled, with ongoing master faults' activity exerting a strong control on the basins' architecture and the available accommodation space. This is reflected by the distribution of the stacked channel deposits in the deepest regions of the half-grabens (Figs. 5, 6b, 6d and 9a). Within this tectonically-controlled setting, a high-energy, multi-channel fluvial system developed, depositing the sand-prone stacked channel deposits of seismic facies D (Figs. 3 and 9a). Based on the presence of red bed intervals and high sand/shale ratios, Den Hartog Jager (1996) suggested these deposits originate from a braided fluvial river system. However, DeVault and Jeremiah (2002) noted that these deposits could equally result from meandering systems with well-drained, oxidised floodplains. Based on the here presented data, the precise fluvial style of this high-energy multi-channel river system cannot be uniquely constrained and remains open for further investigation.

The fluvial system that deposited seismic facies D was active until the middle Berriasian (Fig. 8). A renewed, subordinate phase of global sea-level rise defines the second half of the Berriasian (see Fig. 2), accommodating transgressive conditions that deposited the organic claystones that are correlated to seismic facies C (Fig. 3). Previous studies have identified maximum flooding surfaces in the Nieuwerkerk Formation, supporting this hypothesis (den Hartog Jager, 1996; DeVault and Jeremiah, 2002; Willems et al., 2017). When biostratigraphic data from wells HON-GT-01, HON-GT-02, PNA-GT-02, and VDB-GT-04 (Willems et al., 2017) are integrated with the seismic interpretation of this study, seismic facies C is shown to lie below the *paratollia* maximum flooding surface, which is the oldest flooding surface with data for the Nieuwerkerk Formation. Consequently, the absence of biostratigraphic data below the *paratollia* maximum flooding surface prevents a confident correlation of facies C to a specific maximum flooding surface. Deposited across the entire WNB (Figs. 4 and 5), this intra-Alblasserdam Claystone layer represents one of the most laterally extensive and persistent units identified in this study. It marks a clear transition from the underlying

high-energy, multi-channel river deposits of the lower Alblasserdam Member to the lower-energy, meandering river system that deposited the overlying upper Alblasserdam Member. The consistent seismic character and basin-wide distribution make the intra-Alblasserdam Claystone layer a valuable seismic marker for correlation within the lower half of the Nieuwerkerk Formation. This is particularly important given the lack of biostratigraphic control in the lower Alblasserdam Member, where seismic correlation provides one of the few means to establish reliable stratigraphic frameworks.

5.3.2. Upper Alblasserdam Member

Renewed sea-level fall and decreasing subsidence during the late Berriasian and early Valanginian (see Fig. 2), caused regression and the forestepping of the depositional system at lower energetic regimes (i.e., shallow topographic gradient), giving way to the meandering river environment in which the upper portion of the Alblasserdam Member was deposited (Figs. 8 and 9b). This is reflected by seismic facies B, which represents meandering belt deposits (Figs. 3, 4 and 6c) and a characteristic saw-teeth trend on the GR logs (Figs. 3 and 5), which is typical for fluvial floodplain environments (Cant, 1992). At the time, rifting was still going on, as evidenced by the presence of the alluvial fans/aprons of seismic facies E at the margins of the half-grabens (Figs. 6c and 8b). Yet, tectonic activity was likely much weaker than during the deposition of the underlying deposits as reflected by a shallower topographic relief and gentler slopes, bounding the low-energy floodplain environment in which the meandering river system developed.

The well logs show that roughly 50 to 75% of the half-grabens were filled up by the lower Alblasserdam succession, with marginal depocenters already being filled, as the upper Alblasserdam succession is absent here (Maasland Basin in Fig. 5). Thus, with less physiographic confinement, rivers exploited wider divagation areas favouring a lower-energy meandering versus higher-energy multi-channel system development, and the channel-belt sediments were consequently deposited as isolated sandstone bodies in the shale-prone upper portion of the

Alblasserdam Member. These sandstone bodies are typically found in the central portions of the half-grabens (Figs. 4, 6a, 6c and 9b), where they locally occur as stacked intervals, indicating that tectonic activity still played a significant role during sediment deposition, with active faulting controlling the deepest locations of river incision.

5.3.3. Delft Sandstone Member

Like the upper Alblasserdam Member, the Delft Sandstone Member is defined by seismic facies B (Figs. 3 and 4). Yet, the Delft Sandstone Member shows an increased amount of amalgamated channel fills that display both funnel- and bell-shaped trends on their GR logs (see Fig. 5). The funnel trends are consistent with localized prograding delta systems, whereas the bell-shaped trends may suggest increased tidal influence (Cant, 1992; Fig. 9c). Thus, the sedimentary system probably moved from a fluvial-dominated to a more tidal-dominated delta. Yet, this aspect was not the focus of the current study and would require further detailed examination. The sediments were deposited from the early Valanginian into the Hauterivian (Fig. 8), a period characterised by global sea-level rise and minor subsidence (see Fig. 2). It is likely that the increase in sea level forced the delta front to migrate landward, leading to a backstepping shift in depositional environment, from the meandering river setting that deposited the upper Alblasserdam Member, to a delta-estuary environment during deposition of the Delft Sandstone Member. This caused the diachronous deposition of the Delft Sandstone Member, with the delta-estuary sand front moving from the NE towards the SW (Willems et al., 2017; Vondrak et al., 2018; Fig. 2). It should be noted that, although the strength of rift-related tectonic activity and associated subsidence had strongly decreased, active faulting was still going on at the time of deposition of the Delft Sandstone Member (Weert et al., 2025). Thus, active faulting was partly responsible for the distribution of the depocenters, which were likely located in the deepest sections of the half-grabens (Fig. 6a, 6c and 9c). Yet, with the majority of the half-grabens already filled by the Alblasserdam Member, enough accommodation space was still available, allowing the broad deposition of locally stacked sandstone bodies of the Delft Sandstone Member, which can be associated with a delta-estuary setting (Figs. 4 and 5).

5.3.4. Rodenrijs Claystone Member

On top, the Rodenrijs Claystone Member was deposited from late Valanginian until the late Hauterivian (Fig. 8). It is composed of seismic facies A, which characteristics are typical for shallow-marine environments with a relatively flat seafloor shelfal (e.g., Xu and Haq, 2022), such as a pro-delta to lagoonal setting. The fining upward trend with a sharp base, recorded by the thin sandstone intervals on the GR logs (Fig. 5), can be associated with coastal parasequences, deposited in a retrograding system (Cant, 1992). This is in agreement with recorded sea-level rise at the time, peaking during the Hauterivian (Fig. 2). Rifting was halting during this time, wherefore tectonic influence on the deposition of this member was limited. Like the Delft Sandstone Member, the bottom part of the Rodenrijs Claystone Member is characterised by diachronous deposition, following the landward N to S movement of the coastline (den Hartog Jager, 1996; DeVault and Jeremiah, 2002; Vondrak et al., 2018; Fig. 9c and d). This faster regression prevented the deposition of delta-estuary deposits in the eastern portions of the WNB. Here, the rising sea level outpaced subsidence, leading to the deposition of the Rodenrijs Claystone Member directly on top of the Alblasserdam Member (Fig. 8).

5.4. Fluvial geothermal reservoirs

This study shows that the depositional patterns and sediment composition of fluvial syn-rift deposits are strongly controlled by both tectonics and sea-level fluctuations. Rift-related tectonics shape the basin's geometry, controlling subsidence, associated accommodation space availability, and sedimentary pathways, and thereby influencing

sediment distribution. It also defines topography, which dictates whether a fluvial system forms in a high-energy or low-energy environment. Base-level changes play a critical role in determining the position of the equilibrium point in source-to-sink systems, therefore controlling sediment type, composition, and availability, also driving diachronous sedimentation, as observed in the upper portion of the Nieuwerkerk Formation.

This study of the Nieuwerkerk Formation shows how the interplay between tectonic and climatic factors can cause the development of a wide range of heterogeneous seismic facies. When applying the subdivision of net-to-gross units that was published for the Nieuwerkerk Formation by Donselaar et al. (2015) and updated by Willems et al. (2020), the different seismic facies can be consequently assessed for their geothermal reservoir potential. Based on the sandstone content observed in the GR logs, Willems et al. (2020) divided the Nieuwerkerk Formation into three net-to-gross units: unit 1 is composed of interbedded clay- and siltstones with coal layers that have a low net-to-gross ratio (<15%); unit 2 comprises single meandering channel bodies that are interbedded with clay- and siltstones and have a medium net-to-gross ratio (~15 to 30%); unit 3 contains the vertically stacked channel bodies and has a high net-to-gross ratio (~30 to 60%).

Seismic facies B, D, and F contain vertically stacked channel bodies, which likely feature high connectivity and high net-to-gross ratios. This makes the lower Alblasserdam Member and Delft Sandstone Member particularly promising as geothermal reservoirs. Indeed, the sandstone-prone Delft Sandstone Member is already well-established as a geothermal reservoir, locally reaching net-to-gross ratios of >60% (Willems et al., 2020) and hosting the majority of the geothermal projects in the WNB. However, this study highlights that an interplay of active faulting and sea-level rise influenced the distribution of its sandstone-prone layers, producing a highly heterogeneous reservoir that continues to present challenges for accurate reservoir characterisation. The updated seismic facies library that is presented in this study can help to localise the sandstone-prone layers in more detail, thus reducing the risks for geothermal exploitation of this reservoir. The lower Alblasserdam Member is characterised by stacked multi-channel fluvial sandstone bodies (see Fig. 5), likely with high connectivity, having its sandstone-prone sediments widely distributed throughout the basin (Fig. 6b and d). Consequently, this under-explored interval presents significant potential as a geothermal target. The optimal areas for exploiting this reservoir are the deepest regions of the half-grabens at the time of deposition, which is in agreement with the findings of Weert et al. (2024). Naturally, the presence of volcanic rocks (seismic facies G, see Fig. 3) in the lower Alblasserdam Member should be noted, as they can be confused with the basal sheet sands of seismic facies F, and likely influence local petrophysical properties of the reservoir-seal system.

Less favourable geothermal targets are represented by seismic facies E and facies B in the upper part of the Alblasserdam Member. Indeed, the alluvial fan deposits of seismic facies E are interpreted to be relatively coarse-grained and may locally exhibit favourable porosity, as documented for comparable alluvial fan systems (e.g., Blair and McPherson, 1994; Nichols and Fisher, 2007). However, in the study area these deposits are spatially restricted to areas adjacent to major basin-forming faults. Generally, these regions with neighbouring faults are avoided for geothermal exploitation, as the injection of cold water in these areas may trigger (or induce) seismicity (e.g., Buijze et al., 2019, 2023). Seismic facies B in the upper Alblasserdam Member comprises single meandering channel bodies deposited in a floodplain setting. Here, connectivity between the sandy intervals is inferred to be relatively low, based on medium net-to-gross ratios and analogue studies (e.g., Larue and Hovadik, 2006), although lateral continuity and channel-belt widths remain uncertain, making the upper Alblasserdam Member a less favourable geothermal reservoir.

Seismic facies with high claystone content, such as seismic facies A and C, exhibit low net-to-gross values. The Rodenrijs Claystone Member is recognised as a regional seal, but the intra-Alblasserdam Claystone

Member may also act as an effective secondary seal. This is particularly advantageous when exploiting both the lower Alblasserdam Member and Delft Sandstone Member at the same location. In this framework, the intra-Alblasserdam Claystone layer has the potential to seal the lower Alblasserdam Member, while the Rodenrijs Claystone Member seals the Delft Sandstone Member.

5.5. Methodological insights for future studies

This study should be regarded as a proof of concept, demonstrating the potential of seismic facies analysis combined with seismic attributes for characterising fluvial syn-rift reservoirs. The initial aim of this study was to apply spectral decomposition to visualise the fluvial architecture. However, the vertical and lateral resolution of the available seismic data proved insufficient to reliably resolve individual channel elements using this approach. It should be noted that, where seismic resolution permits, spectral decomposition remains a highly recommended tool for imaging paleolandscapes (e.g., Bauck et al., 2025).

Given these resolution constraints, emphasis was placed on evaluating alternative seismic attributes that could be applied across the available dataset. Several amplitude-based attributes were tested in Petrel, with RMS amplitude extraction yielding the most interpretable results. The effectiveness of this approach strongly depends on the scale of extraction: basin-scale application led to excessive averaging and loss of detail, whereas restricting the analysis to individual sub-basins and stratigraphic intervals preserved amplitude contrasts and produce clearer, more diagnostic patterns.

The used workflow highlighted several limitations. Diachronous horizons were locally difficult to trace consistently across the basin, complicating stratigraphic correlation. Furthermore, the lack of biostratigraphic control in the lower part of the Nieuwerkerk Formation restricts chronostratigraphic resolution. In addition, this work did not look at physical core data, which limits the ability to directly link seismic facies to lithofacies and petrophysical properties, highlighting the value of future core-based studies to complement and validate seismic interpretations.

While the seismic facies identified here were not mapped exhaustively and therefore do not directly delineate reservoir extents, the methodology developed and tested in this study is transferable and can be applied in future work to systematically map sandstone-prone intervals and improve reservoir characterisation in structurally complex rift basins.

6. Conclusions

The subdivision of fluvial geothermal reservoirs into seismic facies provides a valuable framework for interpreting depositional patterns and their potential spatial distribution. In this study, the basin-scale sedimentary infill of the Late Jurassic to Early Cretaceous fluvio-deltaic succession of the Nieuwerkerk Formation in the West Netherlands Basin was interpreted using seismic and well log data. Seven seismic facies were identified and tied to the formation's stratigraphy using available seismic, well log, and biostratigraphic data. Seismic amplitude maps proved useful for interpreting sediment distribution in relation to the basin's architecture. While systematic mapping of seismic facies remains a logical next step for future work, the results presented here demonstrate the influence of tectonic activity and (relative) sea-level fluctuations on depositional styles and reservoir potential.

- The sedimentary architecture and composition of the Nieuwerkerk Formation were strongly influenced by tectonic activity and sea-level fluctuations. Tectonic activity controlled basin geometry and the creation of accommodation space, directly affecting sediment distribution. In contrast, sea-level changes were crucial in defining sediment composition and deposition rates. The conceptual

framework developed in this study highlights how the interaction between tectonic and climatic factors can create a diverse range of depositional environments and contribute to reservoir heterogeneity in subsurface fluvial geothermal reservoirs.

- Integrating tectonic and sedimentary interpretations can provide important insights into the large-scale architecture of fluvial systems in rift basins. Faulting not only controlled sediment accommodation but also influenced the locations of a river system's entry and exit points. Multiple phases of rifting can cause former structural features, such as lengthy half-grabens, relay ramps, and fault offsets, to evolve into areas where the river system entered or exited a graben.
- Within the fluvial reservoirs, intervals comprising stacked sandstone bodies are inferred to offer the highest geothermal potential. In the Nieuwerkerk Formation, these sandstone-rich deposits are found in the lower Alblasserdam Member and Delft Sandstone Member, deposited in high-energy, multi-channel fluvial and delta-plain environments. The stacked channels in these intervals are interpreted to exhibit relatively high connectivity and net-to-gross ratios, making them favourable for geothermal exploitation. In contrast, intervals dominated by alluvial fan deposits or isolated channel bodies are expected to display lower and more variable connectivity, which may reduce reservoir predictability and pose challenges for geothermal exploitation.

The Late Jurassic to Early Cretaceous succession of the Nieuwerkerk Formation in the West Netherlands Basin provides a well-constrained example for advancing the understanding of subsurface fluvial reservoirs in rift settings. While this study does not provide a fully mapped reservoir model, it establishes a transferable seismic-sedimentological workflow that can be applied to systematically identify and map sandstone-prone intervals in complex fluvial reservoirs worldwide.

CRedit authorship contribution statement

Annelotte Weert: Conceptualization, Data curation, Formal analysis, Methodology, Supervision, Validation, Visualization, Writing – original draft. **David Iacopini:** Methodology, Visualization, Writing – original draft. **Stefano Tavani:** Conceptualization, Writing – original draft. **Francesco Vinci:** Conceptualization, Writing – original draft. **Paul van der Vegt:** Writing – original draft. **Kei Ogata:** Conceptualization, Methodology, Supervision, Validation, Visualization, Writing – original draft.

Data repository

All data used in this publication are open access and can be found on NLOG: <https://www.nlog.nl/datacenter/>. An overview of all Dutch seismic and well data in map view can be found here: <https://www.thrmogis.nl/mapviewer>. Present biostratigraphic data for the West Netherlands Basin can be found in the following documents:

- The following scientific publications: DeVault and Jeremiah (2002), Jeremiah et al. (2010), Willems et al. (2017), and Willems et al. (2020).
- Internal PanTerra report G841 (Speksnijder et al., 2011). This study was produced for the CATO project (the Dutch national program of CO₂ capture, transport and storage), and includes seismic analyses and well log correlations.
- Palynological reports produced by Duxbury during the late 90's and early 00's for the NAM (Nederlands Aardolie Maatschappij). The studies focus on the Upper Jurassic and Lower Cretaceous sandstone units in the West Netherlands Basin. Most samples used for these studies were side-wall core and core samples. It should be noted that the reports use the old nomenclature for the stratigraphic sequence, and that these reports are internal NAM reports.
 - o Report 99/131 for the LIR, IJS and BRK wells (Duxbury, 1999a).

- o Report 99/139 which provides a calibration for the Rijswijk Member and top Nieuwerkerk Formation (Duxbury, 1999b).
- o Report 00/152 which provides a biostratigraphic review for the Nieuwerkerk Formation (Duxbury, 2000a).
- o Report 00/162b for wells LIR-02-S1 and IJS-01 (Duxbury, 2000b).
- o Report 01/202 for wells LIR-14 and PRN-01-S1 (Duxbury, 2002).
- The below listed TNO reports. Most of the reports were drafted by Munsterman and provide age assessments based on palynological analyses, focussing on the Upper Jurassic and Lower Cretaceous succession. These reports were made for TNO and most of them are available along with other well data on NLOG.nl.
 - o Offshore hydrocarbon well Q13-05 (Munsterman, 2010).
 - o Geothermal well VDB-GT-04 (Munsterman, 2012).
 - o Hydrocarbon well NMD-03 (Munsterman, 2014a).
 - o Five wells in the Hoeksche Waard (Munsterman, 2014b).
 - o Geothermal well PNA-GT-02 (Munsterman, 2016).
 - o Geothermal well HON-GT-02 (Munsterman, 2017).
 - o Geothermal well LSL-GT-01 (Munsterman, 2018).
 - o Hydrocarbon well EEM-01 (Munsterman, 2019a).
 - o Geothermal wells BRI-GT-01 and MLD-GT-01 (Munsterman, 2019b).
 - o Hydrocarbon well MON-02 (Munsterman, 2019c).
 - o Geothermal well MON-GT-02 (Verreussel, 2024).

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT in order to correct grammar. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Given his role as associate editor, Kei Ogata had no involvement in the peer review of this article and had no access to information regarding its peer review. Full responsibility for the editorial process for this article was delegated to another journal editor. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The used dataset is open accessible via the Dutch Geological Survey (NLOG). Please find all needed information to access the data in the 'Data Repository' section of the manuscript.

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