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Reservoir Geology and Geothermal Potential of the Delft Sandstone Member in the West Netherlands Basin

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ABSTRACT

The Delft Sandstone Member (DSSM) of the Lower Cretaceous Nieuwerkerk Formation in the West Netherlands Basin (WNB) is the target of a technology demonstration project for deep geothermal energy production. A prerequisite for the optimal placement of the geothermal well doublet is the assessment of the depositional setting of the target sandstone interval, and of the spatial distribution, connectivity and internal permeability heterogeneity of the reservoir units therein. To achieve this, a study was done on core, cuttings and well-log data from vintage oil exploration wells in and around the geothermal license area. Integration of the analysis results with earlier studies on the regional geological setting and reprocessed PSDM 3D seismic data show that the DSSM was deposited by a northwest-flowing meandering river system in a SE-NW oriented rift basin. The river deposits are subdivided in three depositional units with varying reservoir properties. Unit 1 is sand-prone and comprises loosely-stacked single-storey meandering river sandstone bodies embedded in a floodplain claystone and siltstone matrix. Unit 2 is a low net-to-gross succession of interbedded claystone, siltstone and coal layers, formed in a wet floodplain and swamp environment. Unit 3 is sand-prone and characterized by multi-storey and laterally-amalgamated meandering river sandstone bodies with minor mudstone floodplain intervals. Based on the good porosity and permeability values and the high lateral and vertical sandstone-to-sandstone connectivity this Unit 3 is considered the most promising target for the placement of geothermal doublets. The results will help broaden the understanding of the reservoir heterogeneity and, hence, reduce uncertainty in geothermal energy projects which target the DSSM.

1. INTRODUCTION

Our present energy system based on fossil fuels is unsustainable because of predicted resource depletion and the large environmental impact of greenhouse-gas emissions. This perception has triggered the research into clean, sustainable energy sources and related reduction of greenhouse gas emissions. Deep geothermal energy production has the potential to become an attractive complementary CO2-neutral energy source. Outstanding issues for a successful and cost-effective geothermal energy production are, among others: (a) the impact of reservoir heterogeneity on total producible geothermal energy, (b) the depletion of the heat source, and decrease of pressure and temperature related to overburden integrity and fault sealing issues, (c) prediction of the total life time of a geothermal reservoir, and (d) scaling and corrosion of production wells.

The Delft Geothermal Project (DAP) was launched as a demonstration project for solutions to technical challenges posed by the cost-effective development of geothermal systems. The project was initiated in 2007 by students, staff, and alumni of the Department of Geoscience and Engineering at the Delft University of Technology, and evolved into a consortium of governmental and industrial partners. The project aims to: (1) build a geothermal system that serves as an energy production facility for heating offices and student houses on the university campus, (2) provide a technology demonstration case for innovative lightweight composite drilling technology, and (3) develop a geothermal research facility.

In 2009, the University was granted an exploration and production license for geothermal energy by the government (Fig. 1). In the 60 km2 license area two geothermal systems owned by glasshouse farmers are operational since 2010 (Fig. 2, wells PNA-GT-01 and PNA-GT-02). Both systems produce water with a temperature of 70 °C from the Delft Sandstone Member (DSSM), which is a Lower Cretaceous (Valanginian) fluvial sandstone formation in the West-Netherlands Basin (WNB). First experiences with the systems indicate that the performance of the geothermal doublets is highly variable. A geothermal doublet comprises a production well for hot water and a re-injection well for the produced and cooled-down water (Figs. 2-3). Both wells are in the same aquifer. The cooled-down water radiates away from the injection well and flows back to the production well. Knowledge of reservoir connectivity between the production and the injection well in the aquifer is therefore essential. However, the targeted fluvial sandstones are highly heterogeneous, and connectivity between individual sandstone bodies over typical doublet distances (1-2 km) is uncertain. Drilling of the two operational geothermal systems in the license area was based on feasibility studies in which well-log and core data were used from nearby oil and gas fields (Delft, Rijswijk, Pijnacker, Moerkapelle, Berkel; Fig. 1). In addition, earlier studies were used to assess the general geological setting of the WNB (Fig. 4; Den Hartog Jager, 1996; Racero-Baena and Drake, 1996; DeVault and Jeremiah, 2002; Jeremiah et al., 2010). However, the oil and gas wells are all located on structural highs in the subsurface, whereas the geothermal wells target the structural lows. In view of the complex, highly variable basin-fill history of the WNB, considerable geological uncertainty is involved in extrapolating subsurface data from the highs to the lows. This specifically concerns the uncertainty associated with the presence and continuity of permeable sandstone in the target aquifer. To reduce this uncertainty, a reservoir characterization study of the DSSM was carried out to assess the spatial distribution of fluvial sandstone bodies, their connectivity and internal permeability heterogeneity. For the present study well-logs, cores and cuttings from wells in the license area and the Moerkapelle area (10 km to the northeast) were re-evaluated, and the results combined with re-processed, pre-stack depth-migrated 3D seismic data. In this paper, the results of this study and their implications for geothermal energy production from the DSSM are discussed.

2. GEOLOGICAL SETTING

The DSSM is part of the Nieuwerkerk Formation and consists of a fluvial succession formed during and after a major Early Cretaceous rifting phase in the WNB. The WNB is a 60-km-wide transtensional basin in the southwest of the Netherlands and the adjacent offshore area and comprises a series of NW-SE trending structural highs and depressions (Fig. 4; Ziegler, 1990). Rifting occurred in several pulses of short duration in the time-span from Kimmeridgian (155 Ma) to Barremian (130 Ma) and the basin was filled syn-tectonically with fluvial sediment. Active rifting decreased in the Hauterivian (135 Ma) and the basin entered a post-rift sag phase. Continued subsidence led to marine transgression, and most of the post-Hauterivian sediments were deposited in a marine setting. The WNB gradually subsided, until the Late Cretaceous Laramide compressional phase started a period of inversion and uplift (Van Wijhe 1987, Den Hartog Jager, 1996). On seismic data, major fault zones display reverse offsets, indicating that older basin-bounding faults were reactivated. Many of the oil-bearing structures (e.g., the pop-up structure that contains the Pijnacker oilfield; Fig. 5) have been formed during this phase (De Jager et al. 1996; Racero Baena and Drake 1996).

2.1 Stratigraphy

The Nieuwerkerk Formation (Fig. 6) consists, from base to top, of the Alblasserdam Member, the DSSM), and the Rodenrijs Claystone Member. The sedimentology of the three members of the Nieuwerkerk Formation has been described by Van Adrichem Boogaert and Kouwe (1993-1997), Den Hartog Jager (1996), DeVault and Jeremiah (2002) and Jeremiah et al. (2010) and is based on core descriptions and gamma-ray logs, complemented with palynological and fossil assemblage data. The present sedimentological description is based on the work of these authors, complemented with results from our analysis of cuttings samples from well DEL-03 in the license area, and on core analysis of the DSSM in the oil exploration well MKP-11 in the Moerkapelle field, 10 km northeast of the license area.

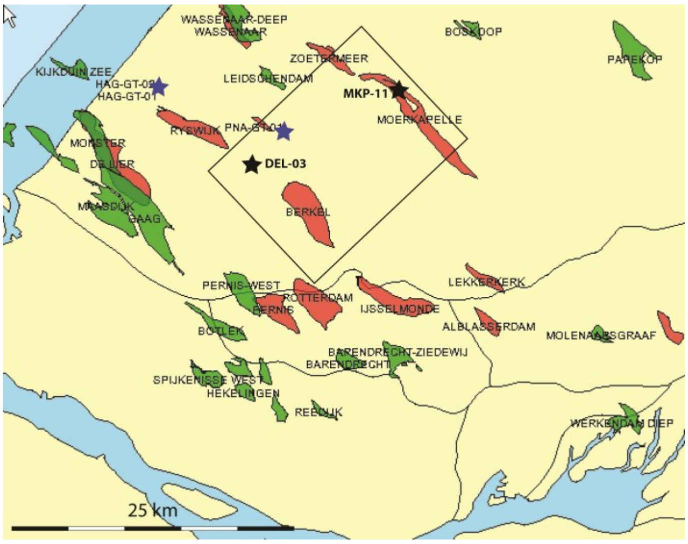

Figure 1: Oil (red) and gas (green) fields in the West Netherlands Basin. Black stars: location of oil wells (DEL-03 and MKP-11) used in this study. Blue stars: location of geothermal wells started in 2010; HAG-GT-01, HAG-GT-02 (The Hague; city heating); PNA-GT-01 (Pijnacker; greenhouse heating). Box: study area. Modified from: www.nlog.nl

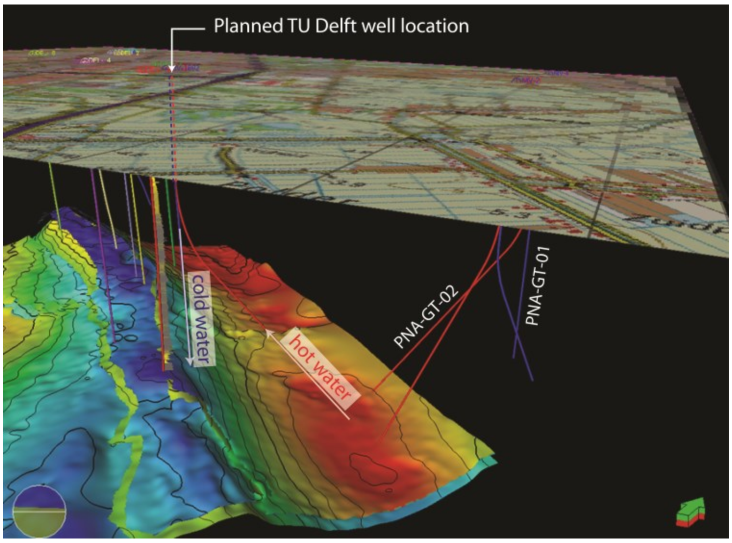

Figure 2: 3D structural model of the DSSM in the study area with trajectories of the planned TU Delft geothermal wells. Wells PNA-GT-01 and PNA-GT-02: producing geothermal doublets.

2.2 Sedimentology

The syn-tectonic Upper Jurassic and Cretaceous basin infill of the WNB (Fig. 6) shows a large-scale transgressive succession up to 3000 m thick with large thickness variations as a result of differential subsidence. The three-fold stratigraphic subdivision comprises, from base to top: (1) fluvial clastic sediments of the Nieuwerkerk Formation (part of the Schieland Group) deposited during the Kimmerian rift phase; (2) marine clastics of the Rijnland Group deposited during the post-rift sag phase, and (3) pelagic carbonates of the Chalk Group (Van Adrichem Boogaert and Kouwe, 1993-1997; Den Hartog Jager, 1996). Good-quality geothermal aquifers are found in the DSSM, and also in the Vlieland Sandstone/Claystone Formation (Rijswijk Sandstone Member, Berkel Sandstone Member) which forms the basal sandy part of the Rijnland Group. Focus of the present study is on the DSSM, the primary target for geothermal energy production on the license area.

2.2.1 Alblasserdam Member

The Alblasserdam Member is present throughout the WNB. The available well-log data and scarce cores indicate that the Member is entirely made up of fluvial deposits. Biostratigraphic data consisting of sporomorph-dominated continental assemblages support this interpretation (DeVault and Jeremiah, 2002). Marine incursions are extremely uncommon in the Alblasserdam Member and restricted to the northern part of the basin. The fluvial succession typically comprises dark-grey to light-grey, red and variegated claystone and siltstone, fine to medium grained sandstone with bed thicknesses up to a few meters, and massive, thick-bedded, coarse-grained sandstone. Coal and lignite beds are associated with the grey claystone intervals. Dispersed lignitic matter, siderite spherulites and concretions are common. Cored sections show extensive mottling of the variegated claystone. Sandstone geometry consists of sheets, isolated or stacked channels (Van Adrichem Boogaert and Kouwe, 1993-1997). A braided-channel type was suggested by Den Hartog Jager (1996) based on the high sandstone/shale ratios. Red beds are commonly observed in overbank settings in the Alblasserdam Member, which lacks coal. The succession is interpreted as fluvial-plain deposits, with sandstone concentrated in mostly channels and crevasse-splays. On the floodplains outside the channels, development of swamps and soils took place. The Alblasserdam Member unconformably overlies Middle Jurassic shallow-marine limestones and shelf mudstones of the Brabant and Werkendam formations, respectively. On some horst blocks however, these formations are entirely truncated and the Alblasserdam Member rests upon the Lower Jurassic Aalburg Formation (DeVault and Jeremiah, 2002). The total thickness is extremely variable, ranging from less than 100 m to more than 1300 m. In the Delft area, the thickness is 300 m in well DEL-03, and about 500 m in well PNA-13, but neither well penetrates the base of the Alblasserdam Member (Fig. 7). This variation is inferred to be controlled by synsedimentary graben formation, with the main faults trending northwest-southeast, and by a rapid pinch-out in a southwesterly direction towards the London-Brabant Massif. Age of the Alblasserdam Member ranges from Portlandian (locally even Kimmeridgian/Oxfordian) to Hauterivian-Barremian (Van Amerom et al., 1976), but these biostratigraphical ages may be inaccurate because of low sporomorph content, especially in the lower, oxidized part of the member (Van Adrichem Boogaert and Kouwe, 1993-1997).

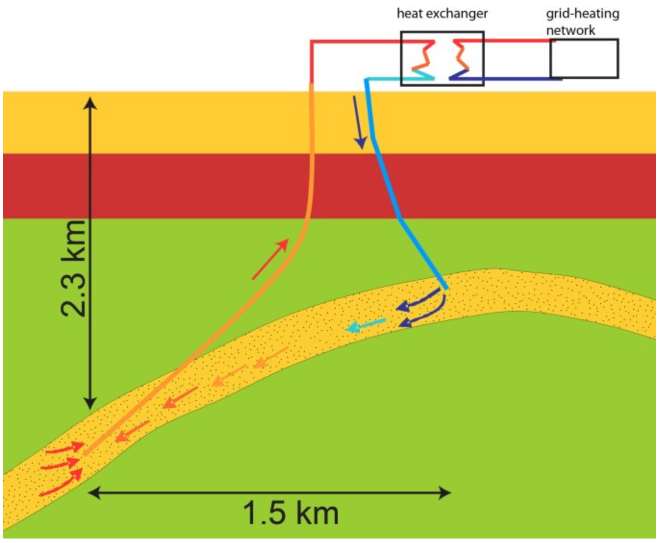

Figure 3: Schematized view of the design of a doublet for production of geothermal energy from an aquifer. A deviated well is used to produce water with a temperature of 65-75 °C from the aquifer at two kilometers depth. At the surface heat is extracted by a heat exchanger to a local grid to sustainably heat buildings and greenhouses. A second well re-injects the cooled-down aquifer water into the same reservoir rock two kilometers away from the production point.

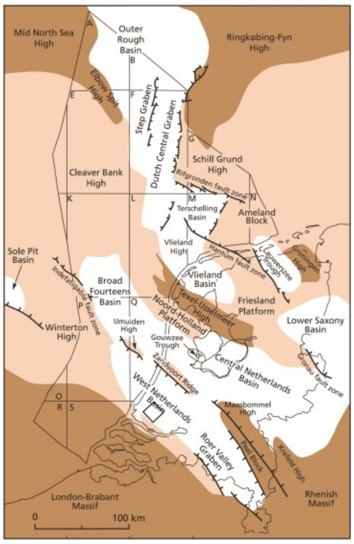

Figure 4: The structural elements of the Netherlands during Late Jurassic - Early Cretaceous. White color indicates the basins; light brown are platforms and dark brown structural highs. Box: license area. (From: Wong, 2007).

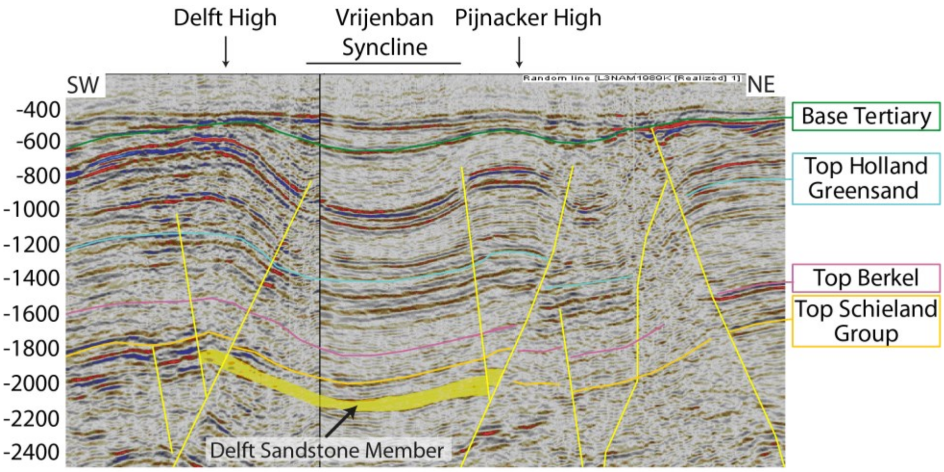

Figure 5: Depth-converted seismic cross-section (depth in m) through the license area shows the horst and graben configuration of the WNB that was later accentuated by inversion. The DSSM sits in a gentle, broad syncline bounded by the Delft High and the Pijnacker High (pop-up structure). Note the subtle thickness difference in the DSSM.

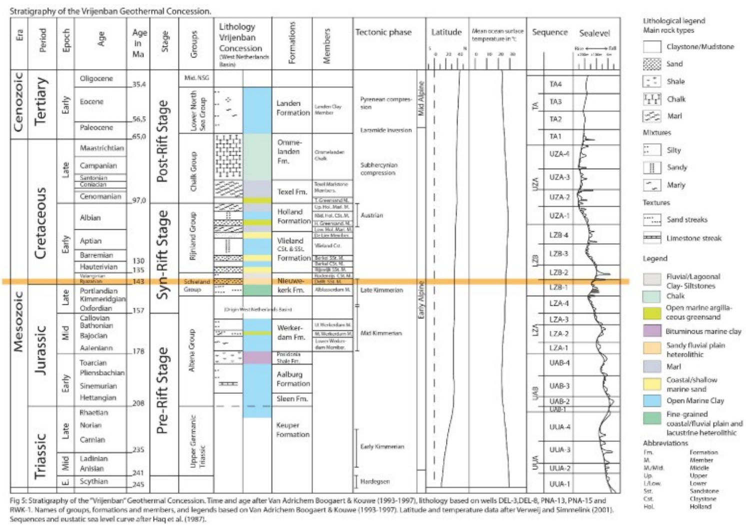

Figure 6: Stratigraphy of the license area. Time and age after Van Adrichem Boogaert and Kouwe (1993-1997), lithology based on wells DEL-3, DEL-8, PNA-13, PNA-15 and RWK-1. Names of groups, formations and members, and legends based on Van Adrichem Boogaert and Kouwe (1993-1997). Latitude and temperature data after Verweij and Simmelink (2001). Sequences and eustatic sea level curve after Haq et al. (1988).

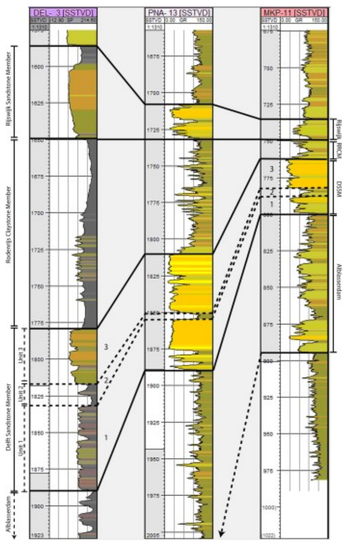

Figure 7: Correlation panel through wells DEL-03, PNA-13 and MKP-11.

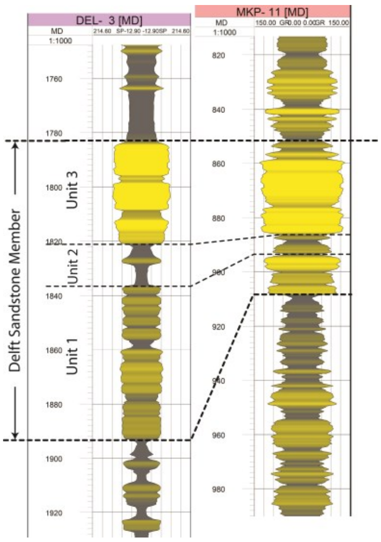

Figure 8: Subdivision of DSSM based on signature of SP-log (well DEL-03), gamma-ray log (well MKP-11), core and cuttings analyses. See Fig. 1 for well location.

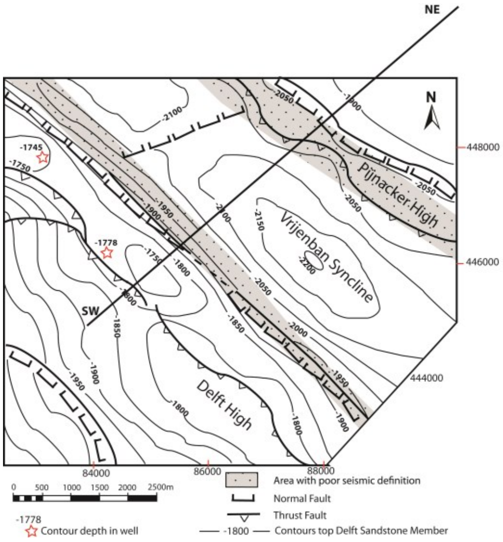

Figure 9: Depth contour map of top DSSM with main structural elements. Map constructed from PSDM and regional time seismic. SW-NE line is location of seismic section in Fig. 5.

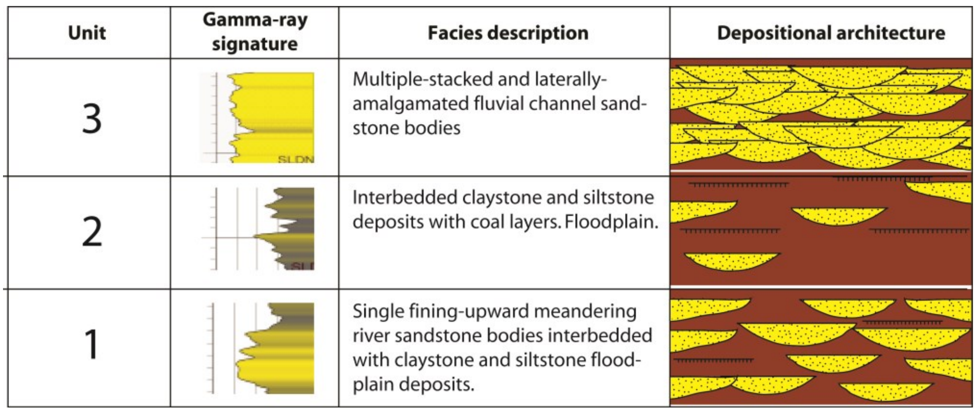

Figure 10: Gamma-ray log signature, facies description and interpreted depositional architecture of the three units in the DSSM.

2.2.2 Delft Sandstone Member

The Delft Sandstone Member (DSSM) conformably overlies the Alblasserdam Member. Occurrence of the DSSM is confined to the western and central parts of the WNB. The DSSM is Valanginian in age, based on sporomorph assemblages (Van Adrichem Boogaert and Kouwe, 1993-1997). The DSSM consists of a fine to coarse-gravelly, light-grey massive sandstone sequence with abundant lignitic matter. This is interpreted as an interval of massive, stacked distributary-channel complexes in a coastal-plain setting (Van Adrichem Boogaert and Kouwe (1993-1997). For the present study detailed core- and cutting analyses were made of the DSSM interval in well MKP-11 in the Moerkapelle oilfield and well DEL-03 in the license area, respectively (Fig. 8). The analyses were used to validate the well-log response in the same wells, and subsequently applied to interpret lithofacies in other non-cored wells. Finally, the well logs were integrated with the reprocessed PSDM 3D seismic, with the aim to visualize the lateral continuity and thickness distribution of the DSSM (Fig. 9). Based on the results, the position of the base and top of the DSSM in gamma-ray logs was defined, which coincide with the base K30 and base K35 sequence boundaries, respectively (DeVault and Jeremiah, 2002). The analyses allow for the subdivision of the DSSM in the license area in three units with varying reservoir properties (Figs. 7 and 10). Unit 1 is the sand-prone lower unit consisting of loosely-stacked single-storey meandering river sandstone bodies with well-preserved fine-grained tops embedded in a floodplain claystone and siltstone matrix (Fig. 11). Unit 2 has an overall low net sand content and consists of interbedded claystone, siltstone and coal layers (Fig. 11), formed in a wet floodplain and swamp environment. Unit 3 is the sand-prone upper unit characterized by stacked, multi-storey and laterally-amalgamated meandering river sandstone bodies with minor mudstone floodplain intervals. The DSSM is conformably overlain by the organic-rich claystone of the Rodenrijs Claystone Member.

2.2.3 Rodenrijs Claystone Member

The Rodenrijs Claystone Member consists of grey lignitic claystone, siltstone and sandstone, characterized by laminated or contorted bedding and lignite/coal beds with well-preserved plant fossils (Van Adrichem Boogaert and Kouwe, 1993-1997). Locally mollusc shells are present. Siderite spherulites and concretions are common. The Rodenrijs Claystone Member shows a characteristic serrate pattern on wireline logs. Core data from the Rotterdam area exhibit fining-upward successions from stacked, cross-bedded fluvial channel sandstone to flood-plain mudstone with occasional crevasse-splay deposits. The fining-upward sequence is capped by coal or thin lacustrine strata. Continued relative sea level rise culminated in lagoonal deposits. Stacked fluvial channel systems with fining-upward sequences and bases eroding flood-plain deposits are also recorded. The predominance of poorly drained flood-plain deposits, crevasse splays, and minor stacked channel deposits suggest a meandering fluvial system (Den Hartog Jager, 1996). Like the DSSM, its distribution is confined to the western and central parts of the WNB. Age of the Rodenrijs Claystone Member is Late Valanginian to Early Hauterivian based on sporomorph analysis (Van Adrichem Boogaert and Kouwe, 1993-1997). A lower-coastal-plain to lagoonal depositional environment is inferred. This proximity to the sea suggests that fining-upward sequences (themselves composed of stacked channel/overbank deposits) are closely linked to relative sea level rise.

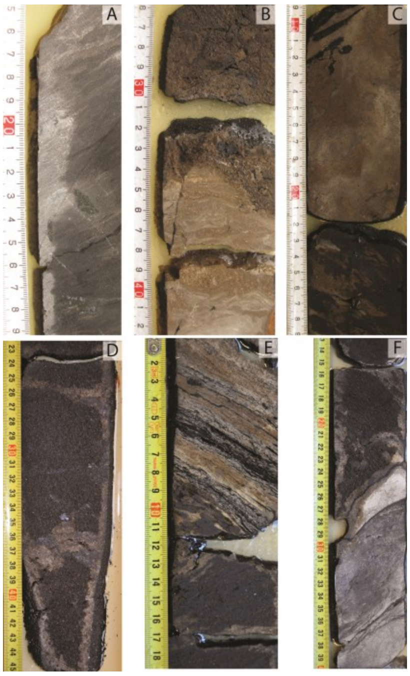

Figure 11: Core photos of the DSSM in well MKP-11. A: Light-grey floodplain siltstone. B: Erosional contact between floodplain siltstone and medium-grained fluvial channel sandstone. Note coal fragments as lag deposit. C: Oil-stained fine to medium-grained fluvial sandstone. D: Oil-stained coarse-grained fluvial sandstone with lighter mud-invasion rim. E: Coal and siltstone laminae; top of fluvial sandstone. F: Erosional contact between grey floodplain siltstone and medium-grained fluvial channel sandstone with coal fragments.

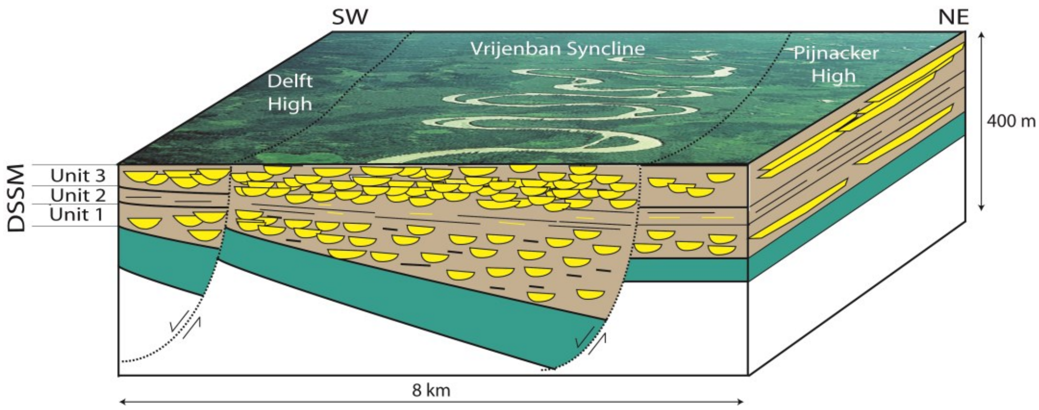

Figure 12: Depositional model for the DSSM in the study area based on analyses of well-logs, cuttings, cores, and on seismic interpretation of fault-conditioned thickness differentiation.

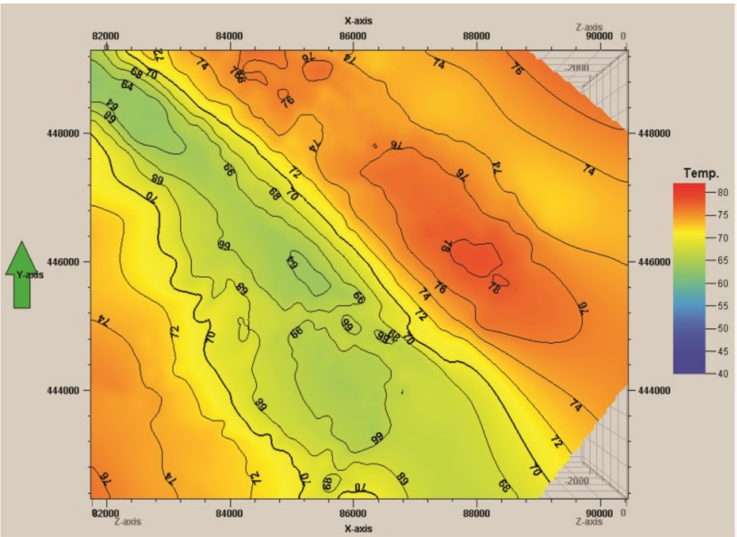

Figure 13: Temperature map of the top DSSM. Temperature in ^oC. Map constructed from interpreted seismic horizon top DSSM and applying the local thermal gradient of 3.11 ^oC per 100 m.

2.2 Depositional model of the DSSM

The lithofacies succession in the license area and surrounding area is primarily controlled by the rate of accommodation development vs. sediment accumulation during synsedimentary tectonic movement along faults that separated the areas southwest of the Delft High and northeast of the Pijnacker High from the low area (Vrijenban Syncline) between the highs (Figs. 2, 5, 9).

Deposition of DSSM Unit 1 was controlled by differential movement along these faults in combination with a rising sea level, i.e., a high rate of accommodation increase which favored the deposition of loosely-stacked, fluvial sandstone bodies with well-preserved fine-grained tops embedded in floodplain fines (Fig. 10). This setting implies low connectivity of the fluvial sandstone bodies. The thickness of Unit 1 increases towards the NE flank of the Delft High (Figs. 7-8), which reflects the synsedimentary activity of this fault during the deposition of Unit 1.

Continued relative sea level rise during deposition of Unit 2 led to temporal paucity of coarser-grained fluvial sediment supply to the area, and to deposition of extensive fine-grained floodplain and swamp sediments. Hence, net sand content of Unit 2 is very low, and excludes this unit as a target for geothermal energy production.

Relative sea level rise decreased during deposition of Unit 3, and led to the deposition of laterally-amalgamated and vertically-stacked fluvial sandstone bodies (Fig. 10). A cross-section through wells MKP-11, PNA-13, and DEL-03 (Fig. 7) shows a rather constant thickness throughout the correlation panel, which reflects that differences in accommodation space were small. The high sand-to-shale ratio and high sandstone connectivity resulted from repeated truncation of fluvial channels into fine-grained sandstone tops and floodplain mudstone in an environment of low accommodation increase. The depositional model resulting from integration of all analysis results shows the sedimentary architecture of the DSSM in the study area (Fig. 12).

3. GEOTHERMAL POTENTIAL

The geothermal potential of the DSSM depends on the total volume of potential reservoir sandstone, on the sandstone permeability and on the temperature of the formation water in the aquifer. Average net sand content (N/G) in the DSSM in the wells is about 0.65, and highest Unit 3. A contour map of the top of the DSSM based on 3D seismic data shows that the depth of the DSSM is between 2000 m and 2300 m in the structural low beneath the license area (Fig. 9). Bottom-hole temperature readings from oil- and gas wells in the region indicate that the geothermal gradient is approximately 3°C/100m, which results in a temperature estimate of 65-75 °C for the formation water in the DSSM (Fig. 13). This is sufficient for use in a low-temperature grid-heating network or a glasshouse heating system. The permeability of the aquifer directly influences the production and re-injection flow rates. Appraisal drilling for hydrocarbons in and around the target area indicated that the DSSM has promising reservoir qualities, i.e., high porosity and permeability. Additional information on spatial and vertical variability was obtained from analyses on core samples and cuttings from wells MKP-11 in the Moerkapelle oil field (10 km to the northeast) and well DEL-03, which indicates that the three units identified in the DSSM have distinctly different porosity and permeability values. The average porosity of Unit 1 is about 19% and the permeability increases from about 90 mD at the base to 295 mD at the top of the unit. Unit 3 contains significantly coarser-grained material than Unit 1, and the average porosity is 30% and the permeability varies between 725 mD and 1130 mD, with the highest permeability found at the base. Unit 2 consists of very fine-grained sediment, has an extremely low porosity and permeability.

4. CONCLUSIONS

The Valanginian (Lower Cretaceous) Delft Sandstone Member (DSSM) of the Nieuwerkerk Formation in the West Netherlands Basin was studied for its potential for deep geothermal energy production. Detailed core and cutting analyses were made of vintage oil fields in the license area to assess the depositional setting of the DSSM and of the spatial distribution, connectivity and internal permeability heterogeneity of the reservoir units therein. Core and cutting analyses were linked to the well-log response and applied to interpret lithofacies in non-cored wells. Integration of the well logs with reprocessed PSDM 3D seismic allowed for the visualization of lateral continuity and thickness distribution of the DSSM. The resulting depositional model shows a subdivision of the DSSM in three units with strongly differing geothermal energy production potential. Units 1 and 3 consist of fluvial sandstone with good porosity and permeability values. Vertical connectivity between both units is very likely impeded by the extremely low porosity and permeability of Unit 2. Integration of own analyses with published data on the regional geological setting suggests that DSSM was deposited by northwest flowing meandering rivers in a SE-NW elongated basin rift basin. A general assumption is that connectivity is highest along the basin axis and decreases perpendicular to the basin elongation. Unit 3 shows a high lateral and vertical sandstone-to-sandstone connectivity and is therefore the most promising target for the placement of geothermal doublets.

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