Available online at www.sciencedirect.com
SCIENCE DIRECT®

Journal of Geochemical Exploration 78–79 (2003) 321–325

JOURNAL OF GEOCHEMICAL EXPLORATION

www.elsevier.com/locate/jgeoexp

Abstract

Development of a freshwater lens in the inverted Broad Fourteens Basin, Netherlands offshore

L. Bouw[a,*], G.H.P. Oude Essink[b,c,1]

[a] *Delft University of Technology, Civil Engineering, Hydrology and Ecology Group, P.O. Box 5048, 2600 GA, Delft, The Netherlands*
[b] *Netherlands Institute of Applied Geosciences (TNO–NITG), Groundwater Department, Princetonlaan 6, P.O. Box 80015, 3508 TA, Utrecht, The Netherlands*
[c] *Free University, Faculty of Earth Sciences, Hydrology and Hydrogeology Department, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands*

Abstract

The Mesozoic Broad Fourteens Basin is a northwest–southeast trending structural element, situated in the southern North Sea, Netherlands offshore. Biodegraded and water-washed oils in the southern Broad Fourteens Basin indicate topography-driven meteoric water flow during Late Cretaceous inversion. Density-driven groundwater flow models support the development of a freshwater lens in the northern Broad Fourteens Basin during Late Cretaceous inversion. Three model scenarios with basin-scale permeabilities and water table heads within the range of most likely values show the possible development of a freshwater lens in the northern Broad Fourteens Basin. The freshwater–saltwater interface is located at a depth of 200–1200 m below mean sea level. Near steady-state flow conditions are reached within 1.5–4 Myr.

Keywords: Basin inversion; Broad Fourteens Basin; Density-driven groundwater flow; Netherlands North Sea; Two-dimensional models

1. Introduction

The Broad Fourteens Basin is a northwest–southeast trending structural element, approximately 120 km long and 45 km wide, situated in the southern North Sea, K and L quadrants Netherlands offshore. The basin was formed during the Mesozoic and it was filled dominantly with claystones. The southwest boundary is formed by a major graben fault, whereas the northeast boundary is formed by a gradual transition to the adjacent platform area. The northern Broad Fourteens Basin is affected especially by salt tectonics and salt diapirism due to the presence of a thick layer of Zechstein evaporites, in contrast to the southern Broad Fourteens Basin where salt movements are less pronounced. The basin was subject to major inversion movements during the Late Cretaceous Sub-Hercynian phase and minor inversion movements during the Early Tertiary Laramide phase. Several publications describe the development and structural geology of the Broad Fourteens Basin in detail (among others, Van Wijhe, 1987a,b; Dronkers and Mrozek, 1991).

Verweij et al. (2000) have presented results of 2D basin modelling of the *southern* Broad Fourteens

* Corresponding author. Tel.: +31-15-278-1462; fax: +31-15-2785915.
E-mail addresses: l.bouw@citg.tudelft.nl (L. Bouw), oudg@geo.vu.nl (G.H.P. Oude Essink).
[1] Fax: +31-20-6462457.

0375-6742/03/$ - see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0375-6742(03)00113-4

Basin and show that the observed biodegradation and water-washed nature of Q1 oil reservoirs (Roelofsen and De Boer, 1991) is consistent with topography-driven meteoric water flow during Late Cretaceous inversion. These Early Cretaceous oil reservoirs of the Vlieland Sandstone Fm are at present-day depths of about 1250–1350 m and the timing of oil emplacement is about 80–60 Myr ago (Roelofsen and De Boer, 1991). Although the Vlieland Sandstone Fm is not present in the northern Broad Fourteens area, the degradation of oil in the southern Broad Fourteens Basin indicates that meteoric water infiltration may also have occurred during inversion of the northern Broad Fourteens Basin.

We present results of 2D density-driven groundwater flow modelling, which support the development of a freshwater lens in the northern Broad Fourteens Basin during Late Cretaceous inversion. Late Cretaceous basin geometry was reconstructed based on regional geological data, well log data (Bouw, 1999), and a detailed southwest–northeast geological cross-section of the northern Broad Fourteens Basin (Bouw and Oude Essink, 2003), after seismic section SNST 83-04 (Van Wijhe, 1987b). Late Cretaceous topography was estimated to be at least 200–300 m. Using this geometry, we studied the possible extension of topography-driven meteoric water infiltration during Late Cretaceous inversion. Three different scenarios were used to show the effects of variations in water table head and basin-scale permeability, within the range of most likely values. Scenario Bre1 has high permeability and a maximum water table head of 275 m; scenario Bre2 has high permeability and a maximum water table head of 137.5 m; and scenario Bre3 has low permeability and a maximum water table head of 275 m. Table 1 lists the used porosity, hydraulic conductivity and anisotropy values, which are based on literature and well log data (Bouw, 1999). Note the two columns in Table 1 with different hydraulic conductivity values, namely one for the low permeability model and one for the high permeability models.

Meteoric water infiltration was calculated with a basin-scale 2D numerical model of density-dependent fluid flow, using the modelling package MOC-DENS3D (Oude Essink, 1999, 2001). The package can only model density-dependent groundwater flow caused by compositional or thermal differences in density. In general, however, thermohaline flow needs to be considered when evaporites are present in the

Table 1
Model parameters for a high and low permeability scenario

Hydrogeological unit	Lithology	Thickness (m)	Porosity (%)	High K (m/s)	Low K (m/s)	Anisotropy
Chalk sediment	Nanno ooze	30	70[a,b]	1×10^{-5}	1×10^{-5}	1.1
Chalk Group	Chalk	100–300	65[b]	1×10^{-7}[c]	2×10^{-6}	1.1[c]
Texel Fm	Limestone and shale	100	50[b]	1×10^{-7}	2×10^{-6}	1
Holland Fm	Marl	100	30	1×10^{-9}[d]	1×10^{-9}	2
Vlieland Claystone Fm	Silty claystone	200–500	30	1×10^{-9}	1×10^{-11}	10
Breeveertien Fm	Sandy claystone	200–400	15–20	1×10^{-7}	5×10^{-10}	100
Altena Group	Claystone	< 950	20[d]	1×10^{-9}	5×10^{-11}	10
Upper Germanic Trias Group	Claystone, limestone, and salt	250	5[e]	1×10^{-7}[e]	5×10^{-10}	50[e]
Main Buntsandstein Subgroup	Claystone and sandstone	200	20[e]	5×10^{-7}[f,g]	1×10^{-7}	100
Lower Buntsandstein Fm	Silty claystone	350	20[d]	1×10^{-7}[d]	5×10^{-10}	10
Zechstein Group	Salt, anhydrite and limestone	>300	2	8×10^{-11}[h]	1×10^{-13}	1.0

The longitudinal dispersivity is set equal to 10 m, while the ratio of transversal to longitudinal dispersivity is 0.1.
[a] Cornford (1994).
[b] Einsele (1992).
[c] Price (1987).
[d] Beekman et al. (1989).
[e] Spain and Conrad (1997).
[f] Purvis and Okkerman (1996).
[g] Dronkers and Mrozek (1991).
[h] Tóth (1995).

model domain, because of density effects caused by both high thermal conductivity and dissolution of evaporites. In the case of the northern Broad Fourteens Basin, thermal effects can most likely be neglected, and only density effects due to dissolution of evaporites are taken into account. Temperature effects on fluid density are counteracted by the background salinity increase with depth (Bjørlykke and Gran, 1994), which is present in the system. Temperature effects on density-driven flow were also neglected because of a lack of (reliable) data on temperature gradients in the basin centre and thermal conductivities of relevant lithostratigraphic units.

The chloride concentration of infiltrating meteoric water was set to 100 mg Cl/l. The concentration of lithostratigraphic units was set initially to 18,630 mg Cl/l (equal to seawater composition), except for the Zechstein Group. The Zechstein fluid composition was set to a fixed concentration of 218,920 mg Cl/l, which is similar to analysed fluids of the Zechstein Group at the Leman Field, UK offshore, with 411,280 mg/l TDS (Sullivan et al., 1994). The initial salinity distribution before the actual simulation of meteoric water infiltration is obviously very difficult to determine. In this study, it is generated by simulating the mixing of fluids by molecular diffusion only. At the beginning of this simulation, groundwater in the Zechstein Group is entirely brine and the groundwater in the units above it range from saline to brackish. After a certain time, molecular diffusion has caused an increase in chloride concentration in hydrogeological units overlying the Zechstein Group. Within a few hundreds to more than 1000 m vertically above the Zechstein Group, fluid salinity is increased (Fig. 1, top left profile). This increased salinity above evaporites is analogous to other areas in the North Sea where underlying evaporites and diapirs are present, as described by Bjørlykke and Gran (1994).

The meteoric water inflow is modelled through a specified freshwater head along the entire upper boundary of the inverted basin. For all three scenarios the freshwater head is highest in the basin centre and declines smoothly towards the edges of the inverted basin. The lower no-flow boundary is chosen within

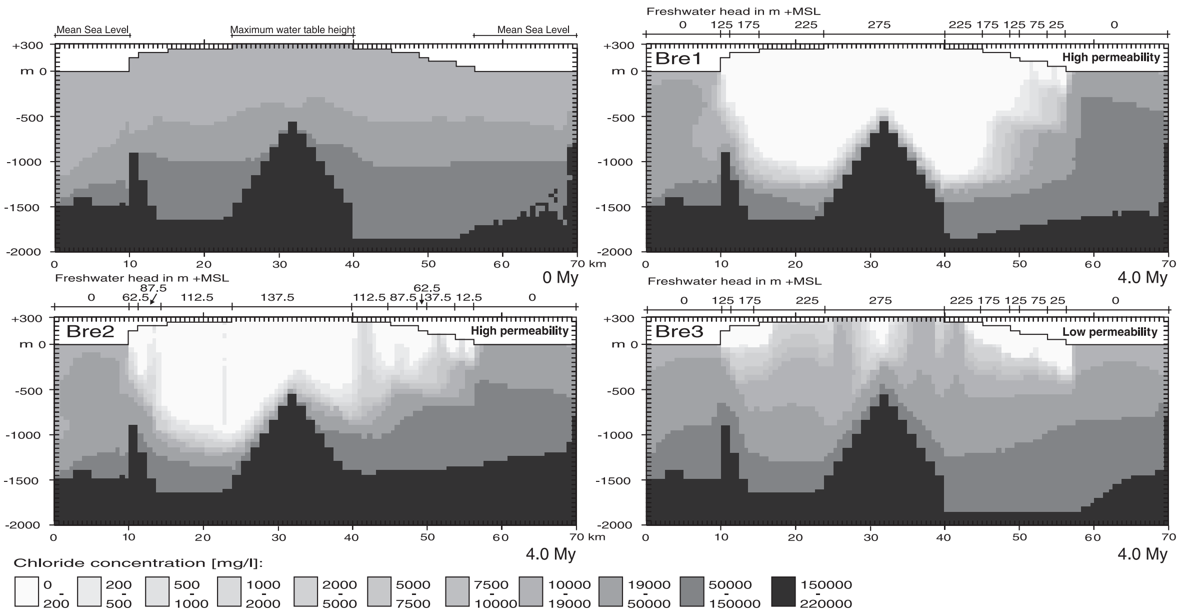

Fig. 1. Model results of density-dependent simulations of topography-driven meteoric water infiltration show chloride concentration distribution in the northern Broad Fourteens Basin during Late Cretaceous inversion. Top left profile shows initial chloride distribution due to diffusion of saline Zechstein fluids only. Top right profile shows model scenario Bre1, high basin-scale permeability and maximum water table head 275 m. Bottom left profile shows model scenario Bre2, high basin-scale permeability and maximum water table head 137.5 m. Bottom right profile shows model scenario Bre3, low basin-scale permeability and maximum water table head 275 m.

the Zechstein Group, which has a low permeability and is continuously present along the cross-section. The lateral boundaries are modelled as hydrostatic pressure boundaries.

2. Results

The results of model scenarios are sensitive to the distribution of the Zechstein Group (shown in Fig. 1 by the black area with highest chloride concentration), the chosen freshwater head and selected permeability values. Fig. 1 gives the initial chloride concentration distribution (top left profile) and model results of scenarios Bre1, Bre2 and Bre3, which show the development of a freshwater lens (top right, bottom left, and bottom right profiles, respectively). Model scenarios Bre1 and Bre2 (high permeability) both show the development of a "freshwater" lens (Fig. 1, white area), which reaches the Zechstein Group in the basin centre. Near steady state is reached within 1.5 Myr for scenario Bre1 (high freshwater head) and the freshwater–saltwater interface is located at a depth of about 1200 m below mean sea level. Near steady state is reached within 4 Myr for scenario Bre2 (low freshwater head), and the freshwater–saltwater interface is located at a depth of 500–1100 m. Model scenario Bre3 (low permeability, high freshwater head) shows the development of a "freshwater" lens with limited extent, which does not reach the Zechstein Group in the basin centre. Near steady state is reached within 3 Myr for model scenario Bre3, and the freshwater–saltwater interface is located at a depth of about 200 m below mean sea level.

3. Discussion and conclusions

During Late Cretaceous basin inversion, a freshwater lens was most likely developed in the northern Broad Fourteens Basin, as supported by the biodegraded and water-washed nature of oils in the southern Broad Fourteens Basin. A density-dependent fluid flow model of the northern Broad Fourteens Basin indicates that meteoric water infiltration could have reached and subroded the uplifted Zechstein salts in the basin centre. Model results indicate that the freshwater–saltwater water interface is located at a depth of about 200–1200 m. Near steady-state flow conditions are reached within 1.5–4 Myr.

Acknowledgements

This publication is based on work carried out at the Netherlands Institute of Applied Geosciences (TNO–NITG), under supervision of J.M. Verweij, H.J. Simmelink and R.T. van Balen, and their contribution is gratefully acknowledged.

References

Beekman, H.E., Glasbergen, P., Slot, A.F.M., Prins, H.F., 1989. Inventarisatie en evaluatie van geohydrologische gegevens van Noordoost en Oost Nederland ten behoeve van het onderzoek naar de opberging van radioactief afval in zoutformaties. RIVM, Bilthoven, the Netherlands. 242 pp.

Bjørlykke, K., Gran, K., 1994. Salinity variations in North Sea formation waters: implications for large-scale fluid movements. Marine and Petroleum Geology 11, 5–9.

Bouw, L., 1999. Geology, hydrogeology and hydrodynamics of the northern Broad Fourteens Basin, southern North Sea: a conceptual model. MSc thesis, Department of Earth Sciences, Utrecht University and Netherlands Institute of Applied Geosciences (TNO–NITG), Utrecht, the Netherlands. 160 pp.

Bouw, L., Oude Essink, G.H.P., 2003. Fluid flow in the northern Broad Fourteens Basin during Late Cretaceous inversion, accepted for publication in the special issue of the Netherlands Journal of Geosciences 82 ('Geofluids in the Netherlands').

Cornford, C., 1994. Mandal–Ekofisk (!) Petroleum system in the Central Graben of the North Sea. In: Magoon, L.B., Dow, W.G. (Eds.), The Petroleum System—from Source to Trap. AAPG Memoir, vol. 60. Tulsa, USA, pp. 537–571.

Dronkers, A.J., Mrozek, F.J., 1991. Inverted basins of the Netherlands. First Break 9, 409–425.

Einsele, G., 1992. Sedimentary Basins: Evolution, Facies and Sediment Budget. Springer-Verlag, Berlin, Germany. 628 pp.

Oude Essink, G.H.P., 1999. Simulating 3D density-dependent groundwater flow: the adapted MOC3D. In: De Breuck, W., Walschot, L. (Eds.), Proceedings of the 15th Salt Water Intrusion Meeting. Natuur-en Geneeskundig Vennootschap, Ghent, Belgium, pp. 69–79.

Oude Essink, G.H.P., 2001. Salt water intrusion in a three-dimensional groundwater system in the Netherlands: a numerical study. Transport in Porous Media 43, 137–158.

Price, M., 1987. Fluid flow in the Chalk of England. In: Goff, J.C., Williams, B.P.J. (Eds.), Fluid Flow in Sedimentary Basins and Aquifers. Geological Society Special Publication, vol. 34. Blackwell, Oxford, pp. 141–156.

Purvis, K., Okkerman, J.A., 1996. Inversion of reservoir quality by early diagenesis: an example from the Triassic Buntsandstein, offshore the Netherlands. In: Rondeel, H.E., Batjes, D.A.J., Nieuwenhuijs, W.H. (Eds.), Geology of Gas and Oil under the Netherlands. Kluwer Academic Publishing, Dordrecht, the Netherlands, pp. 179–189.

Roelofsen, J.W., De Boer, W.D., 1991. Geology of the Lower Cretaceous Q/1 oil-fields, Broad Fourteens Basin, The Netherlands. In: Spencer, A.M. (Ed.), Generation, Accumulation and Production of Europe's Hydrocarbons. Special Publication of the European Association of Petroleum Geoscientists, vol. 1. Oxford Univ. Press, Oxford, United Kingdom, pp. 203–216.

Spain, D.R., Conrad, P.C., 1997. Quantitative analysis of top-seal capacity: offshore Netherlands, southern North Sea. Geologie en Mijnbouw 76, 217–226.

Sullivan, M.D., Haszeldine, R.S., Boyce, A.J., Rogers, G., Fallick, A.E., 1994. Late anhydrite cements mark basin inversion: isotopic and formation water evidence, Rotliegend Sandstone, North Sea. Marine and Petroleum Geology 11, 46–54.

Tóth, J., 1995. Hydraulic continuity in large sedimentary basins. Hydrogeology Journal 3, 4–16.

Van Wijhe, D.H., 1987a. The structural evolution of the Broad Fourteens Basin. In: Brooks, J., Glennie, K.W. (Eds.), Petroleum Geology of Northwest Europe. Graham and Trotman, London, United Kingdom, pp. 315–323.

Van Wijhe, D.H., 1987b. Structural evolution of inverted basins in the Dutch offshore. Tectonophysics 137, 171–219.

Verweij, J.M., Simmelink, H.J., David, P., Van Balen, R.T., Van Bergen, F., Van Wees, J.D.A.M., 2000. Geodynamic and hydrodynamic evolution of the Broad Fourteens Basin and the development of its petroleum systems: an integrated 2D basin modelling approach. Journal of Geochemical Exploration 69–70, 635–639.