Stellingen behorend bij het proefschrift:

Reservoir-geologische aspecten van productiviteit en connectiviteit van gas reservoirs in Nederland

Harm.W. Frikken

1. Bij de ontwikkeling van gas reservoirs in Nederland is het risico van potentieel slecht productie gedrag lange tijd onderschat. Naast stratigrafische en sedimentologische compartimentalisatie, is de aanwezigheid van sub-seismische 'strike-slip' breuken een van de hoofdoorzaken van problematische productiviteit en connectiviteit (c.f. Hoofdstukken 2, 3, 4 en 6 van dit proefschrift).

2. De aanwezigheid en de invloed van diaklazen in gas reservoirs in Nederland is lange tijd onderschat. Diaklazen zijn echter alomtegenwoordig in de minder poreuze en ondoorlatbare gesteenten (c.f. Hoofdstuk 5 van dit proefschrift).

3. Zelfs bij het uitoefenen van een hobby door een academicus moet de kritische houding en de wetenschappelijke integriteit bewaard blijven. Professor A. Köbben doet in zijn boek De onwelkome boodschap, Utrecht 1999, een uitspraak die gebaseerd is op een gerucht zonder verificatie: "Een ander tekenend geval betreft een geoloog die het door hem aangetoonde verband tussen aardbevingen en gasboringen van de NAM niet mocht publiceren".

Deze uitspraak bevat drie onjuistheden. De betreffende geoloog beoogt het verband juist te relativeren, heeft daar nooit over willen publiceren en is daarvan nooit door de NAM weghouden.

4. Het is van groot belang dat wetenschappers zich goed laten voorlichten om te voorkomen dat het publiek wordt misleid.

"Onttrekking van delfstoffen veroorzaakt het inzakken van de bodem waardoor slipvlakken gereactiveerd kunnen worden en materiaal gaat afrijden.....Een leek kan immers constateren dat indien een rechte bodem tot een kom inzakt, de bodem van de kom langer is dan de oorspronkelijke horizontale bodem. Uitrekking van de bodem kan leiden tot scheurvorming in huizen en gebouwen" (Professor mr. J.M. van Dunné, Erasmus Universiteit Rotterdam, Schriftelijk Commentaar Mijnbouwket, Wetsontwerp 26 219, 1998).

De berekende, verwachte maximale bodemdaling door gaswinning boven het Groningen veld bedraagt 38 cm over een straal van ca. 15 km. De hieraan gekoppelde helling bedraagt slechts 0,001 graad en de rek in de bodem van de kom slechts 5 micrometer.

5. Locale, extreme gesteente mechanische instabiliteit wordt, meer dan bodemdaling, gezien als de hoofdoorzaak van aardrillingen in noordoost Nederland.

‘Wrench’ tectoniek resulteert in aanzienlijke horizontale spanningsverschillen in de ondergrond van Nederland, hetgeen tot uiting komt door de aanwezigheid van open diaklazen en de ellipticititeit van boorgaten. De oriëntatie hiervan is in overeenstemming met de hedendaagse maximum horizontale spanning (c.f. Hoofdstukken 3 en 5 van dit proefschrift).

6. Het gebruik van veldgegevens in het modelleren van reservoirs dient met de grootste omzichtigheid te geschieden. De omvang van ontsluitingen is veelal te kleinschalig in vergelijking met de totale afmetingen van de sedimentluchamen. Analogeën voor de spatiëring van diaklazen vertonen echter een fractale relatie hetgeen heeft geresulteerd in een nieuw model om de onderlinge afstand van grotere open diaklazen te voorspellen (c.f. Hoofdstukken 5 en 6 van dit proefschrift).

7. De toepassing van geïnverteerde seismische data kan worden beschouwd als een doorbraak in het modelleren van reservoirs. Het verschaf een beter inzicht in de structuur en de kwaliteit van deze reservoirs, resulterend in meer nauwkeurige schattingen van gas volumes, productiviteit en connectiviteit (c.f. Hoofdstuk 6 van dit proefschrift).

9. “I am only too painfully aware how increasingly difficult it is to keep pace with the ever-rising tide of geological literature. A very large mass of the writing is utterly worthless and it may be quite profitable both in time and temper to be left unread”.
(Sir Archibald Geikie, Director General of the Geological Surveys of Great Britain and Ireland, The founders of geology, 1897).
In bijna honderd jaar is er veelal weinig veranderd.

10. De ethiek van onze samenleving staat op het spel door over-tolerantie in de rechtspraak. Maatschappelijke dienstverlening voor moord kan leiden tot agressie bij nabestaanden en is grensverlagend voor potentiële criminelen.
“Nabestaanden worden veelal erger gestraft dan de misdadigers” (Gerrit Krol, Voor wie kwaad wil: een bespiegeling over de doodstraf, 1990).


12. In het algemeen zijn televisie programma’s van zeer slechte kwaliteit, zelfs het nieuws wordt beoordeeld op commerciële waarde. Veel producenten en artiesten zijn in zoete drugshandelaren, ze houden het volk verslaafd en dom, enkel voor geld en roem.

13. Het is verbazendwekkend dat sommige bekende juristen, die er in slagen om ernstige misdadigers vrij te pleiten, geen problemen hebben met hun geweten.
“Every lawyer at least once feels himself crossing a line, which he really doesn’t mean to cross. If he crosses it enough times, he should be confronted with his self-esteem, otherwise he will end up as a shark in dirty water.” (John Grisham, The Rainmaker, 1997).

‘La mort par violence et guerre augmentera, tant et si bien qu’à la fin seulement les morts seront innocents’ (Albert Camus, Reflections sur la guillotine, 1957).

15. Ondanks voordurende beloften door het management van oliemaatschappijen gedurende ten minste twee decennia worden de bijdragen van specialisten zoals geologen nog steeds ondergewaardeerd en blijven hun carrière mogelijkheden doorgaans beperkt.
‘The intrapreneur distinguishes himself from the manager. The manager organises; the intrapreneur creates and innovates’ (G. Pinchot, Intrapreneuring, 1985).

16. Een kleine groep fundamentalisten doet verwoed pogingen om onder andere de Flora en Fauna Wet te veranderen om de jacht te verbieden. Ook een mogelijk verbod op het boren naar ‘Waddengas’ wordt gedichtwoord door een kleine groep individuen. We lijken te leven in een democratie die geregeerd wordt door een dictatuur van minderheden die mede door de welvaart, voortvloeiend uit de aardgas opbrengsten, tijd lijken te vinden om te ageren.
Reservoir-geological aspects of productivity and connectivity of gasfields in the Netherlands

Harm W. Friksen
Reservoir-geological aspects of productivity and connectivity of gasfields in the Netherlands

THESIS

For obtaining the degree of doctor at the Technical University Delft
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Harm W. Frikken
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Voor mijn zoon Joeri
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Summary

"Only by perseverance the snail reached Noah's ark".  

As most of the world’s hydrocarbon producing basins have reached maturation (in exploration and development), the major reserves have probably been found and new although smaller reserves are found around and within existing fields, as is the case in the Netherlands.

The policy of the Nederlandse Aardolie Maatschappij B.V. is to develop and produce these smaller gas reserves to save the remaining reserves of the giant Groningen field as much as possible. To date some 160 additional, smaller and predominantly Rotliegend, aeolian/fluvial Slochteren Sandstone reservoirs have been discovered and developed in the on- and offshore Netherlands. This in addition to ca. 25 mature reservoirs mainly contained in Zechstein carbonate platform, slope and basin deposits and Carboniferous fluvial channel sandstones.

Development of the smaller reservoirs carries a significant economic risk as a result of relatively small volumes, increased development costs, low gas price, lack of infrastructure and above all, unexpected productivity and connectivity problems.

The purpose of this thesis is to compile an overview of the various reservoir-geological conditions that contribute to the anomalously poor production behaviour of a range of different types of reservoirs, i.e. unexpected and disappointing productivity and connectivity. Furthermore, it is intended to propose methods and techniques to identify, predict and remedy the problems and to further reduce the business risk associated with field developments.

These methods and techniques require a multi-disciplinary approach involving sedimentology, stratigraphy, structural geology, geophysics, petrophysics, reservoir-engineering, production-technology and drilling-engineering. A large part of this thesis covers the analysis of the characteristics of problematically behaving Rotliegend Slochteren Sandstone reservoirs. In addition, the characteristics of the mature and frequently problematically behaving Zechstein carbonate reservoirs and Carboniferous fluvial channel reservoirs are covered in detail. Analysis of the regional wrench tectonic framework and its impact on reservoir behaviour in the NE Netherlands forms a key element of this thesis. Wrench tectonic signatures
have previously been reported from the Netherlands and the North Sea Basin, e.g. Ziegler 1975, 1978 and Speksnijder 1987.

Previous publications on wrench tectonics in the Netherlands have not provided a clear link between wrench tectonic activity and reservoir architecture and behaviour. Analysis and synthesis of the regional structural deformation history of the north Netherlands has confirmed that a complex interplay of wrench tectonics has been active from Carboniferous times till present. Analysis by the author of the characteristics of anomalous production behaviour of reservoirs in combination with the interpretation of wrench tectonic signatures has resulted in:

1) Revision of the concepts regarding depositional patterns of Carboniferous, Rotliegend and Zechstein reservoirs and hence reservoir architecture,
2) Identification of the presence of sub-seismic, cataclastic and compartmentalising strike-slip faults, in which signatures from Borehole Image logs and seismic attribute maps play a dominant role.
3) Identification of the fact that natural closed and open fractures are ubiquitous in the less porous and tight reservoirs in the whole of the NE Netherlands.
4) A novel model for predicting the spacing of major open fracture systems. These fractures strike dominantly N-S, i.e. largely parallel to the present-day maximum horizontal stress.
5) Optimised development techniques for problematically behaving reservoirs.
6) Recognition of prospectivity in areas where previously no reservoir development was expected, i.e. off-platform carbonate build-ups.

**Rotliegend reservoirs**

A number of the smaller, mainly offshore Rotliegend reservoirs, consisting of aeolian and fluvial deposits, show disappointing production behaviour when compared to the proven predictable production characteristics of larger fields. A number of conditions have been recognised to be responsible for the anomalous behaviour of the smaller fields. These fields contain a smaller percentage of highly permeable aeolian layers and more frequent intercalations of laterally extensive shale barriers than the larger fields.
The anomalies can be explained by differences in the palaeo-topographical settings. For example, the giant onshore Groningen field was situated in a topographically higher area during deposition with a lower ground water table and therefore more susceptible to reworking of the initially waterlaid sands by aeolian activity. The smaller fields are predominantly located in palaeo-low areas, which may well be explained by syn-sedimentary faulting. These fields are characterised by the presence of dominantly fluvial wadi deposits, a relatively low percentage of scattered, thin and discontinuous aeolian dune sands and relatively large amounts of laterally extensive shale barriers (deposited by playa lake incursions and large desert ponds).

Strong differential depletion occurs within the aeolian sand layers together with frequently insufficient intra-reservoir (cross)flow from the bulk of the poorly permeable waterlaid sands. In addition, compartmentalisation of the smaller fields, which are bounded by major faults, by cataclastic, sub-seismic strike-slip faults has been recognised as one of the major causes of their disappointing productivity and connectivity.

In 1992, for the first time in NAM’s production history, sub-seismic strike-slip faults, as a result of wrench tectonics, were recognised in the K15-FG field by means of signatures from borehole image logs, calibrated by core data, lineations on seismic attribute maps and production data. This novel technique of identifying sub-seismic fault compartments has thereafter been successfully applied to explain anomalous behaviour of several reservoirs.

Discovery wells often provide the only opportunity to gather information on which reservoir performance predictions are based. Therefore, despite the attitude of cost reductions in the oil industry, prolonged production testing and analysis, coring and extensive well logging including borehole image logs are extremely important to gather upfront data for production performance predictions.

Three-dimensional computer modelling is being applied to characterise and analyse the anomalously behaving reservoirs in detail. Remedial activities are applied successfully like: 1) Sub-horizontal drilling, to penetrate the full gas column in strongly layered reservoirs, to access different fault compartments and to intercept possibly larger numbers of scattered highly permeable
aeolian layers, 2) Improved selection of drilling fluids to avoid formation impairment, 3) Improved completion design, e.g. the application of slotted liners, and 4) Hydraulic fracturing to enlarge the inflow area and to overcome wellbore impairment and the effects of near-wellbore fault/fracture zones. Based on the observations, conclusions and predictions as mentioned above, a number of small Rotliegend gas field discoveries in the offshore Netherlands have not been brought into production yet because of severe doubt about productivity and connectivity behaviour, lack of effective development strategy and hence their economic attractiveness.

**Zechstein reservoirs**

Besides underperforming Rotliegend reservoirs, the matured Zechstein 2 carbonate reservoirs of SE Drenthe consisting of platform, slope and basinal deposits have been subject to extensive study. Economic development of these overall tight reservoirs has been dependent on wells encountering major open fracture systems. Analysis by the author of the regional structural deformation history of the NE Netherlands has revealed that a complex interplay of wrench tectonics has been active from the Carboniferous to the present. Two major NW-SE striking, near parallel wrench fault systems are present, i.e. the Holsloot-W Groningen and the Coevorden-Hantum fault zones.

Analysis of cores and borehole image logs has shown an abundance of synthetic and antithetic Riedel shear fractures, extensional fractures and fractures and faults with reverse offsets, their configuration being in reconciliation with the deformational features related to largely NW-SE oriented dextral wrenching. Out of some 6000 measured fractures, approximately 20% of fractures are open, dominantly oriented N-S and this orientation is largely parallel to the present-day maximum horizontal stress in the NE Netherlands. Indications are presented that the major wrench fault systems have dominated depositional patterns during Carboniferous, Rotliegend and Zechstein times.

A novel model is presented, predicting the spacing of the major open fracture systems in Zechstein reservoirs, based on wrench tectonic signatures in the subsurface and supported by a number of world-wide outcrop analogues. The
model is validated by the results of eight recently drilled, E-W oriented horizontal wells, intersecting open ‘mega’ fractures and showing up to 300-fold productivity improvements. Furthermore, the possible presence of off-platform carbonate build-ups, locally triggered by syn-sedimentary wrench faulting which generated subtle palaeo-highs within the Zechstein basin, has been analysed and this has led to extensive appraisal of additional reserves.

**Carboniferous reservoirs**

New concepts are presented regarding the architecture and re-development of the mature Carboniferous fluvial channel reservoirs. Repetitive sequences of highly productive, laterally very extensive, multi-storey braided channel sand complexes have been identified, overlain by less productive, laterally discontinuous meandering channel deposits, the latter representing labyrinthine reservoirs. Syn-sedimentary faulting has been identified as well as sub-seismic faulting, which explains the poor connectivity of the laterally extensive braided channel deposits in some of these reservoirs.

A field case is presented in which the revised concept of reservoir architecture is applied, by means of three-dimensional computer modelling and the use of geometrical data sets from outcrop analogues. The model has been validated and refined by a novel technique, i.e. importing seismic inversion data which are translated into porosity and net sand distribution into the 3D model. The study acts as a pilot for further development of a large number of Carboniferous reservoirs.

**Computer modelling**

As mentioned before, advanced three-dimensional computer modelling by means of the Shell proprietary software-modelling package Geocap is increasingly being applied to analyse problematically producing reservoirs. This is done to obtain a match with the actual production performance of the reservoirs, to locate undrained parts of the reservoirs and for the optimisation of location, number, orientation and type of potential infill wells. For this purpose it is of importance to have accurate knowledge of the different facies types and their stacking patterns, obtained from cores, wireline logs and especially borehole image log data.
Furthermore, it is important to obtain detailed understanding of the overall reservoir architecture, including compartmentalisation by sub-seismic faulting and to have access to statistical outcrop data sets of the 3D geometries of the different facies types. These geometrical data sets are obtained from literature and extra-mural fieldwork research. However, such data sets should be treated with great caution. Firstly, it is very important to select the proper type of analogue for the modelling exercises. Secondly, frequently large uncertainties exist in the lateral extent of deposits in outcrops, the size of outcrops frequently being too small to provide a true representation of the geometries. The large scatter in width-thickness data sets of Rotliegend and Carboniferous facies types is representative for these uncertainties. However, outcrop analogues used for the prediction of distribution and spacing of fractures like in e.g. the Zechstein carbonates are envisaged to carry far less uncertainty because the data sets show a clear fractal relationship.

One of the key technology drivers in NAM is to integrate seismic, reservoir-geological, petrophysical and reservoir-engineering data in the building of 3D reservoir models. Increased computing power and improved algorithms enable inversion of good quality seismic reflectivity data into acoustic impedance data and finally into reservoir properties. This provides the novel and unique opportunity to predict laterally varying reservoir properties like thickness, porosity and net-to-gross ratios. These predictions from seismic data assist in refining/updating the conventional, prior 3D reservoir models, based only on geological and petrophysical data. These data sets result in more accurate calculations of field volumetrics, to validate any anomalous production behaviour and improved input into dynamic reservoir simulations.

This novel technique of seismically constrained 3D reservoir modelling has been recently applied in NAM (Friksen et al. 1999 and Chapter 6). The technique furthermore provides a unique opportunity for appraisal of so far undrilled blocks, in which the seismic inversion data indicate areas with better reservoir quality, providing the basis for more refined well planning. The results of the studies contained in this thesis are aimed at and already contributing to: 1) Overall improvement of field development strategy of new and matured reservoirs, 2) Enhance the accuracy of production performance
predictions, 3) Optimise the location, number, orientation and type of wells and 4) Enhance the overall recovery efficiency of reservoirs.
Samenvatting

Naar alle waarschijnlijkheid zijn de grotere gas en olie voorkomens in de voornaamste bekkens ter wereld reeds ontdekt en in ontwikkeling. Dit is ook het geval in het grote NW Europese Bekken. Nieuwe, hoewel kleinere voorkomens van gas en olie worden heden ten dage voornamelijk nog aangetroffen rond en binnen in de bestaande velden. Het beleid van de Nederlandse Aardolie Maatschappij B.V. is erop gericht om deze nieuwe relatief kleinere voorkomens snel en adequaat te ontwikkelen en te produceren om de reserves van het reusachtige Groningen gasveld zo veel mogelijk te sparen.


De ontwikkeling van de kleinere reservoirs draagt een aanzienlijk economisch risico met zich mee als gevolg van de aanwezigheid van relatief kleine gas volumes, toenemende ontwikkeling kosten, een relatief lage gas prijs, nog niet aangelegde pijpleidingen en bovenal veelal onverwachte problemen met de productiviteit en connectiviteit van het gas in deze velden.

De doelstelling van het onderzoek dat ten grondslag ligt aan dit proefschrift is het samenstellen van een overzicht van de verscheidenheid aan reservoir-geologische omstandigheden die bijdragen aan het afwijkend slechte productie gedrag van verschillende types gasvelden. Een verdere doelstelling is het analyseren van methoden en technieken om de onverwachte en teleurstellende productiviteit en connectiviteit te identifieren, voorspellen en te verhelpen om zodoende het economische risico van het ontwikkelen van potentiële problematisch producerende gasvelden te verkleinen. Deze methoden en technieken vereisen een multi-disciplinaire aanpak waaronder sedimentologie, stratigrafie, structurele geologie, geofysica, petrofysica, mijnbouwkunde, productie technologie en boor technologie. Het hoofdonderdeel van dit proefschrift omvat de analyse van karakteristieken van problematisch producerende Rotliegend Slochteren Zandsteen reservoirs, die een significante bedrijfswaarde vormen voor de Nederlandse Aardolie Maatschappij en de Nederlandse Staat. Tevens worden in detail de karakteristieken beschreven van de Zechstein kalksteen reservoirs en de zandsteen reservoirs van Karboon.

Tot dusver is er in publicaties geen duidelijk verband gelegd tussen ver wring ing tektoniek en de gevolgen daarvan op de opbouw, structuur en het gedrag van gas reservoirs. Analyse en synthese van de regionale structurele vervorming geschiedenis van noord Nederland heeft bevestigd dat een ingewikkelde wisselwerking van ver wring ing tektoniek heeft plaatsgevonden vanaf het Karboon tot op heden. Analyse door de auteur van dit proefschrift van het afwijkende productie gedrag van gasvelden in combinatie met de interpretatie van ver wring ing tektoniek heeft geleid tot:

1) Herziening van het begrip omtrent de afzettings patronen van reservoirs van Karboon, Rotliegend en Zechstein ouderdom en dus de interne opbouw van de gasvelden.
2) Identificatie van de aanwezigheid van sub-seismische, cataclastische en afsluitende horizontale verschuivingbreuken die de connectiviteit in gasvelden belemmeren dan wel verhinderen. De kenmerken zoals waargenomen van ultra- akoustische boorgatmetingen en specifieke eigenschappen van seismische kaarten spelen in de herkenning een dominante rol.
3) Identificatie van het feit dat natuurlijke gesloten en open diaklaas systemen alomtegenwoordig zijn in de minder poreuze en nagenoeg ondoorlaatbare reservoirs in geheel noordoost Nederland.
4) Een nieuw model om de onderlinge afstand te voorspellen van de grotere open diaklaas systemen. Deze hebben een dominante noord-zuid strekking en zijn nagenoeg parallel aan de hedendaagse maximum horizontale spanning in de ondergrond.
5) Verbeterde ontwikkeling technieken voor problematisch producerende velden.
6) Herkenning van mogelijke gasvelden in gebieden waar voorheen de aanwezigheid van reservoir ontwikkeling niet was voorzien, met name kalksteen riffen in het bekken zelf. Deze worden geacht te zijn ontstaan onder locale ondiep water omstandigheden als gevolg van bijvoorbeeld plooiing, resulterend uit ver wring ing tektoniek tijdens de afzetting.
Rotliegend reservoirs

Een aantal van de kleinere, voornamelijk uit de kust liggende Rotliegend reservoirs vertonen teleurstellend productiegedrag vergeleken met het aangetoonde betere productiegedrag van de grotere velden. De reservoirs bevatten gas in fossiele zandafzettingen van woestijnduinen (aeolisch) en woestijnrivieren uit het Rotliegend Tijdperk. Een aantal omstandigheden zijn herkend als zijnde verantwoordelijk voor het afwijkende gedrag van deze kleinere velden. Deze reservoirs bevatten een kleiner percentage hoogdoorlaatbare lagen van aeolische oorsprong en meer frequent voorkomende, voor gas ondoordringbare schalielagen dan de grotere velden. Deze verschillen worden verklaard door verschillen in palaeo-topografische omstandigheden. Bijvoorbeeld, het gebied van het reusachtige Groninger gasveld was tijdens de afzetting van het zand een relatief topografisch hooggelegen gebied met een lagere grondwater spiegel en daardoor was het zand meer ontvankelijk voor transport door wind.

De zandsteen van de kleinere velden op het continentale plaat is voornamelijk afgezet in palaeo-topografisch lager gelegen gebieden, hetgeen verklaard wordt door activiteit van breuken tijdens de afzetting. Deze kleinere velden worden gekarakteriseerd door de aanwezigheid van voornamelijk woestijnrivier afzettingen, een laag percentage woestijnduin afzettingen en een relatief hoog percentage wijdverbreide kleilagen, afgezet in woestijnmeren en door tijdelijke transgressie van het destijds aangrenzende zeegebied. De hoogdoorlaatbare, relatief dun-gelaagde woestijnduin afzettingen vertonen een aanzienlijk groter drukverval dan de minder doorlaatbare rivierzand afzettingen en deze laatste vertonen onvoldoende verticale toestroming van gas naar de hoogdoorlaatbare lagen. Ook is de aanwezigheid van afsluitende, sub-seismische horizontale verschuivingbreuken waargenomen in de kleinere velden. Deze worden gezien als een van de hoofdoorzaken van de teleurstellende productiviteit en connectiviteit.

Voor het eerst in de productie geschiedenis van NAM werden in 1992 dit soort breuken herkend in het K15-FG veld door middel van boorkern gegevens, afwijkende productie data, kenmerken van ultra-acoustische boorgat metingen en subtiële kenmerken van seismische kaarten. Deze nieuwe technieken om sub-seismische, geïsoleerde breukblokken te identificeren zijn vervolgens
voortdurend succesvol toegepast om afwijkend productie gedrag van verscheidene velden te verklaren.

Het boorgat dat leidt tot de ontdekking van een nieuw gasveld is veleal de enige bron om informatie te vergaren omtrent voorspellingen wat betreft productie gedrag. Ondanks de neiging tot kostenbesparing in de olie industrie is het van cruciaal belang om voldoende boorkernen te nemen, uitgebreide metingen te doen in de putten en uitgebreide productie testen uit te voeren om vooraf voldoende gegevens te verzamelen om zodoende het toekomstige productie gedrag te kunnen voorspellen.

Drie-dimensionaal modelleren wordt toegepast met behulp van geavanceerde computer applicaties om afwijkend producerende reservoirs in detail te analyseren en karakteriseren. Een aantal maatregelen worden getroffen om de productie problemen te verhelpen: 1) Sub-horizontaal boren in sterk gelaagde reservoirs om een mogelijk groter aantal hoogdoorlaatbare aeolische zandlagen te aan te sluiten, om verschillende geïsoleerde breukblokken aan te sluiten en daarnaast ook nog de gehele gaskolom te penetreren, 2) Verbeterde samenstelling van boorspoeling om te verhinderen dat de doorlaatbaarheid van de zandlagen rond het boorgat wordt aangetast, 3) Verbeteringen in de bebuizing van de boorgaten, onder andere het toepassen van bebuizing met sleuven, en 4) Het hydraulisch breken van het reservoir gesteente om het instroming oppervlak te vergroten, om mechanische schade aan het boorgat te compenseren en om nabijgelegen breuk en diaklaas zones te doorbreken.

Gebaseerd op de bovengenoemde observaties, gevolgtrekkingen en voorspellingen is het tot ontwikkeling brengen van een aantal kleinere gasvelden op het continentale plat uitgesteld. Dit vanwege ernstige twijfel omtrent het productiviteitgedrag en dus de economische haalbaarheid van het ontwikkelen van deze kleinere gasvelden.

**Zechstein reservoirs**

Naast de studie van afwijkend producerende Rotliegend reservoirs zijn ook de reeds langer producerende Zechstein kalksteen reservoirs onderwerp geweest van uitgebreide studie. De economische ontwikkeling van deze in het algemeen laag-poreuze en bijzonder slecht doorlaatbare reservoirs is lange tijd volledig afhankelijk geweest van het bij toeval aanboren van open breuk systemen. De
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auteur heeft de regionale structurele vervorming geschiedenis van noordoost Nederland in detail bestudeerd. Uit deze studie is naar voren gekomen dat een complexe wisselwerking van verwringing tectoniek heeft plaatsgevonden vanuit het Karboon tot op heden. Twee grootschalige NW-ZO gerichte, nagenoeg evenwijdige verwringing breuksystemen zijn aanwezig in de ondergrond van noordoost Nederland, met name de Holsloot - West Groningen en het Coevorden - Hantum breuksystemen.

Analyse van boorkernen en ultra-akoestische boorgat metingen heeft naar voren gebracht dat synthetische en antithetische Riedel diaklaas patronen, samen met open en overschuiving-diaklaazen en -breuken alom aanwezig zijn in de ondergrond. De configuratie van de diaklaas systemen is in overeenstemming met de deformatie karakteristieken gerelateerd aan hoofdzakelijk NW-ZO gerichte rechts-laterale verwringing tectoniek. De orientatie van ongeveer 6000 diaklaazen is gemeten. Hiervan bestaat ongeveer 20% uit open diaklaazen met een hoofdzakelijk noord-zuid strekking en deze orientatie is in overeenstemming met en nagenoeg evenwijdig aan de huidige maximale horizontale spanning in de ondergrond van noordwest Europa. Aanwijzingen worden naar voren gebracht dat de grootschalige verwringing breuken de afzetting patronen hebben beïnvloed tijdens het Karboon, het Rotliegend en tijdens het Zechstein.

Een nieuw model wordt gepresenteerd betreffende de voorspelling van onderlinge afstanden van de grotere open diaklaas systemen in de Zechstein reservoirs. Dit model is gebaseerd op de kenmerken van verwringing tectoniek in de ondergrond en wordt ondersteund door een aantal wereldwijde analoge diaklaas systemen aangetroffen in ontsluitingen. Het model is bekrachtigd door de resultaten van acht recentelijk geboorde, oost-west georiënteerde horizontale boorputten, dwars op de richting van de open diaklaazen. De putten hebben open diaklaazen aangetroffen, gekenmerkt door aanzienlijke boorspoeling verliezen, en vertonen verbeteringen in productiviteit tot een factor 300. Verder is de aanwezigheid van individuele kalksteenrif structuren geobserveerd die voorkomen in het bekken zelf, ten noorden van de bekkenrand. Deze structuren zijn waarschijnlijk ontstaan in locaal palaeo-topografisch hoger gelegen gebieden, die zijn geïnduceerd door breukwerking tijdens de afzetting. Deze structuren kunnen mogelijk aanzienlijk additionele gas reserves gaan opleveren.


**Karboon reservoirs**

Nieuwe begrippen worden beschreven betreffende het karakter en de opbouw van de reeds langer producerende Karboon reservoirs die bestaan uit rivierzand afzettingen. Deze nieuwe feiten leveren een aanzienlijke bijdrage tot een mogelijke verdere ontwikkeling van een aantal van de problematisch producerende reservoirs om zodoende een toevoeging aan de huidige gasreserves op te leveren. Opeenvolgingen zijn geïdentificeerd van hoog productieve, tot 35 m dikke, opeengestapelde zandpakketten, welke in het algemeen zijwaarts zeer uitgebreid zijn. Deze worden afgewisseld met minder productieve, zijwaarts aanzienlijk minder uitgebreide en slechts 2-10 m dikke zandlagen.

De dikkere en uitgebreide zanden zijn afgezet door vlechttende en verwilderde rivieren, de dunnere en lateraal discontinuë de zanden daarentegen door meanderende rivieren. Dit laatste type discontinuïte Nederland zanden, omsloten door klein-werking tijdens de afzetting is geïdentificeerd hetgeen in enkele gevallen geleid heeft tot laterale discontinuïteit van de kwalitatief betere, dikkere en bredere zandpakketten. Ook is de aanwezigheid van kleine sub-seismische breuken geïdentificeerd met een spronghoogte tot maximaal 15 m. Deze breukjes hebben veelal ook een beduidende horizontale verschuiving ondergaan en vormen derhalve effectieve barrières voor gas doorstroming. De aanwezigheid van dit soort breukjes kan worden herkend door middel van subtiele lineaties op seismische kaarten.

De afwijkende productiviteit en connectiviteit van sommige boorputten wordt verklaard door de aanwezigheid van dit soort kleine maar veelal effectief afsluitende breuken.

Een voorbeeld wordt gepresenteerd aan de hand van een studie van een slecht producerend gasveld, waarin de nieuwe begrippen ten aanzien van de reservoir opbouw zijn toegepast. Dit samen met drie-dimensionaal computer modellering en het gebruik van geometrische data sets van analoge gesteenten uit ontsluitingen. Het model is verfijnd en bekrachtigd door een nieuwe techniek, het inbrengen van geïnverteerde seismische gegevens die vertaald zijn in laterale variatie in porositeit en zand verdeling. De betreffende studie is bedoeld als een proefonderzoek voor het optimaliseren van de ontwikkeling van een groot aantal Karboon reservoirs.
Drie-dimensionaal computer modellering

Zoals eerder vermeld worden geavanceerde drie-dimensionale computer modellen meer en meer toegepast, door middel van het Shell gepatenteerde modellering pakket Geocap, voor het analyseren van problematisch producerende velden. Dit wordt gedaan om overeenstemming te vinden tussen het afwijkende productiegedrag van reservoirs en de modellen, om zodoende niet aangesloten delen van de velden te lokaliseren en voor optimalisatie van de locatie, het aantal, de orientatie en het type van mogelijke toekomstige ontwikkeling boorputten. Het is voor dit doel van groot belang om een nauwkeurige kennis te hebben van de verschillende gesteente types en hun onderlinge relatie, hetgeen wordt verkregen aan de hand van studie van boorkernen en in het bijzonder ultra-akoestische en weerstand metingen in boorgaten.

Verder is het van groot belang om een zo gedetailleerd mogelijk beeld te hebben van de interne opbouw van de reservoirs, inclusief het mogelijk voorkomen van nauwelijks waarnembare breukjes die de toestroming van gas verhinderen. Ook statistische gegevens omtrent de dikte-breedte verhouding van de verschillende gesteente types zijn van groot belang voor het verfijnen van de computer modellen. Hoewel, zulke statistische data moeten met de grootste voorzichtigheid worden toegepast. Ten eerste is de keuze van een vergelijkbaar gesteente type in ontsluitingen van cruciaal belang. Ten tweede is de verbreiding van bijvoorbeeld rivierzand afzettingen veelal groter dan de omvang van ontsluitingen waardoor een volkomen verkeerd beeld kan worden geschetst van de ondergrond reservoirs in de modellen. Desalniettemin, de analoge veldgegevens, die gebruikt zijn in het nieuw voorgestelde model voor de voorspelling van de onderlinge afstand van open diaklas systemen voor de Zechstein kalksteen reservoirs, worden als minder onzeker beschouwd vanwege het feit dat de verschillende voorbeelden een verhouding vertonen die fractaal is.

Een van de technologische uitdagingen binnen NAM is het integreren van seismische, reservoir-geologische, petrofysische en productie gegevens in de constructie van de 3D modellen. De sterk toegenomen capaciteit van computers en verfijnde algoritmes maken het heden ten dage mogelijk om seismische reflectie gegevens te inverteren naar akoestische impedantie en uiteindelijk in reservoir kwaliteit zoals porositeit en netto-zand verdeling. Dit biedt een unieke
mogelijkheid om laterale variaties te voorspellen in reservoir kwaliteit. Deze indicaties vanuit seismische gegevens dragen bij tot het verfijnen van de conventionele reservoir modellen die gebaseerd zijn op geologische en petrofysische gegevens. Dit soort data sets bieden de mogelijkheid tot meer nauwkeurige berekeningen van gas volumes, het bekrachtigen van afwijkend productie gedrag en verbeterde invoer voor dynamische reservoir simulatie studies.

Deze nieuwe techniek van modellering, gestuurd door seismische gegevens, is recentelijk toegepast binnen NAM (Friksen et al. 1999 en Hoofdstuk 6). De techniek wordt momenteel succesvol toegepast op afwijkend producerende Rotliegend en Karboon reservoirs om de modellen te verfijnen. Deze techniek biedt een unieke gelegenheid om locaties van toekomstige boorputten te optimaliseren, ook voor nog niet aangeboorde reservoir blokken, waarbij seismische inverse gegevens gebieden lokaliseren met betere reservoir kwaliteit. De resultaten van de studies zoals beschreven in dit proefschrift worden in toenemende mate gebruikt voor: 1) Het verbeteren van de ontwikkelingstrategie voor nog niet ontwikkelde en reeds producerende reservoirs, 2) Het vergroten van de nauwkeurigheid van het voorspellen van productiegedrag van velden, 3) Het optimaliseren van de locatie, het aantal, de orientatie en het type boorputten, en 4) Het verhogen van de doelmatigheid om gas reservoirs zo optimaal mogelijk te exploiteren.
CHAPTER 1

Introduction

1.1 History of oil and gas in the Netherlands.

The first hydrocarbons in the Netherlands were encountered by an exploration well in 1923 in the E Netherlands (well Corle), where small amounts of oil were found in Zechstein anhydrite and Carboniferous sandstones. A demonstration well in 1938 in The Hague (well de Mient) encountered indications of oil in Tertiary deposits. From 1937 onwards some 12 exploration wells were drilled in the Coevorden area of SE Drenthe, where gravitational anomalies had been detected previously (Dorsman 1954). This led to the first economic hydrocarbon discovery in 1943 near Schoonebeek where oil was found in the Lower Cretaceous Bentheim Sandstone.

The gravitational anomaly in the SE Drenthe/Twente area coincided with the E-W oriented Saxony fold trend, which continues into the W German Osnabrueck area, where outcrops are present ranging from Carboniferous to Cretaceous. This area proved to represent a continuously active zone in the geological history of NW Europe, e.g. it forms the southern margin of Rotliegend and Coppershale deposits, it is the location of the E-W trending Zechstein 2 Carbonate platform edge (van der Baan 1990) and it formed the southern margin of the Lower Saxony Basin.

The oil discovery in Schoonebeek was followed by the discovery of several oil accumulations in Lower Cretaceous sandstone reservoirs in the W Netherlands. The first natural gas (not associated with oil) was found in 1948 in Upper Permian Zechstein 2 Carbonates (Main Dolomite) in the Coevorden area, east of Schoonebeek. Successively, a number of gas fields were discovered in the SE Drenthe and Twente areas including gas in Zechstein 3 Carbonates (Platy Dolomite) and fluvial Carboniferous Sandstones (1955, near Rossem Weerselo in Twente).

The discovery of the giant Groningen field took place in 1959 with gas accumulation in the Lower Permian, Upper Rotliegend Slochteren Sandstone (aeolian-fluvial deposits), followed by the discovery of a range of smaller Slochteren Sandstone gas reservoirs surrounding the Groningen field.
In the early 1970's offshore gas fields were discovered mainly in the K and L blocks, with the bulk of gas reserves in the Slochteren Sandstone.

1.2 Outline and purpose of this thesis

As many of the world's hydrocarbon producing basins have reached maturation, the major reservoirs have probably been discovered and developed. Most of the new reserves are found in and around existing larger fields, as is the case in the Netherlands. To date some 160 'smaller’ gas fields have been discovered in the on- and offshore areas.

Figure 1 provides an overview of hydrocarbon reservoirs of the on- and offshore Netherlands, operated by the Nederlandse Aardolie Maatschappij B.V. (NAM). Active exploration is ongoing and many smaller fields are still being discovered and developed to temporarily save the reserves of the giant Groningen gas field. In addition, over the last few years activities are strongly focussed on the so-called 'old gasses’ in Zechstein and Carboniferous reservoirs for re-development purposes to improve the ultimate recovery from these old reservoirs.

However, despite more profound knowledge about the subsurface and advanced technology, development of such 'small fields' carries a significant economic risk as a result of the presence of relatively small gas volumes, low gas price, increased development costs, frequent lack of infrastructure and above all unexpected productivity and connectivity problems.

An increasing number of multi-disciplinary studies is required for optimised development of new fields and to increase the ultimate recovery of matured, producing fields. The studies include 3-dimensional computer modelling and reservoir simulations, combined with extensive literature study and fieldwork on outcrop analogues, to obtain a better understanding of the frequently complex reservoir architecture and related production behaviour.

This thesis compiles the results of applied reservoir-geological research on identification, analysis, remedy and prediction of productivity and connectivity problems of reservoirs in the Netherlands on- and offshore. The results of the studies are applied in the optimisation of field development strategy of new and existing reservoirs. The thesis is fully written 'a titre personnel'; all work, statements and conclusions drawn in this thesis are the responsibility of the author, unless referenced. The geophysical and reservoir-engineering data used
and applied in this study have been provided by acknowledged colleagues, however, the interpretation of features from the data are on account of the author. The published papers that form the framework of this thesis have been presented at international conferences and workshops.

The papers are the result of research carried out in the periods 1991-1993 and 1995-1998 during employment with the Nederlandse Aardolie Maatschappij B.V. The GIIP figures quoted should not be treated as absolute values because volumetric calculations are continuously subject to revision. This thesis compiles state of the art methods and techniques of reservoir-geology, as well as multidisciplinary, novel ideas with respect to: 1) sedimentology, 2) stratigraphy, 3) diagenesis, 4) petrophysics, 5) geophysics, 6) structural geology, 7) reservoir-engineering, 8) production-technology and 9) drilling-engineering.

The initiation of this thesis was formed by a reservoir-geological, multidisciplinary study to analyse the background of problematic production behaviour of a number of small, recently discovered Rotliegend gas reservoirs in the central Dutch offshore K and L blocks (Fig.1). Subsequently, studies have focussed on the matured reservoirs contained in Zechstein 2 carbonate deposits and Carboniferous fluvial channel deposits. Study of these latter, frequently problematically behaving reservoirs had been postponed over the last decades because of the known extreme complexity of reservoir architecture.

Besides significant differences in diagenesis in the offshore Rotliegend reservoirs, differences in reservoir architecture were detected between the larger fields, which behave like tank-type reservoirs and the smaller fields, which showed unexpected anomalous behaviour. The larger fields consist of dominantly aeolian, high permeability sands. However, the small fields frequently comprise a strong dual porosity system with thin, high permeability streaks, alternating with thicker packages of low permeability waterlaid sands and comprising more frequent, although only up to 1-2 m thin shale separations when compared to the larger fields. It appeared that reservoir compartmentalisation by sub-seismic faults was a major cause of the anomalous behaviour of smaller fields. Because of the relatively high net-gross-ratio, i.e. relatively few and thin shale layers, clay-smear along these faults is not regarded as a main cause for the sealing capacity of the small faults.
Cataclasism as a result of strike-slip was recognised from thin sections in the offshore area that led to the concept that strike-slip faulting is the main cause of reservoir compartmentalisation. Wrench tectonic signatures had already been reported from the Netherlands and the North Sea Basin by e.g. Ziegler 1975, 1978 and Speksnijder 1987. However, Harding 1990 in his paper strongly objected and called their interpretation and that of many other authors a misjudgement of the tectonic setting. Harding proposed a number of criteria for proper identification of wrench fault systems. In the Dutch offshore, however, not all the criteria were recognised. Anastomosing fault zones characteristic for transcurrent fault zones, together with dextral displacement of NE-SW trending faults along the major NW-SE wrench faults, en-echelon fault patterns and the presence of reverse faults were nevertheless identified.

Lineations on seismic attribute maps were initially disregarded by geophysicist as being artefacts from processing and overburden anomalies like Zechstein 3 carbonate rafts floating in the salt caprock. However, incorporation of these sub-seismic features in subsurface models provided a match with the actual production performance of a number of reservoirs. Furthermore, fracture and fault orientations as obtained from interpretation of some of the first Borehole Image logs were identified to be in line with the orientation of deformation features related to dominantly NW-SE oriented dextral wrenching in the offshore area and the orientation of lineations on seismic attribute maps.

The presence and sealing character of such cataclastic strike-slip faults was proven by the results of a challenging infill well in the offshore K15-FG field which showed insignificant depletion of only some 20 bar compared to an expected 130 bar depletion as calculated from the 250 bar depletion in a neighbouring well. This also indicated that such initially sealing strike-slip faults show partial seal-failure after significant pressure depletion between the different fault compartments. Furthermore, a sub-horizontal sidetrack in the offshore L13-FE field across a number of mapped lineations, together with improved selection of drilling fluid and completion design, resulted in significant improvement of connectivity when compared to the original problematically producing well, which was located in an isolated fault block.

The theory of wrench tectonic control on offshore reservoir architecture and behaviour was proven during a study of anomalously behaving Zechstein carbonate reservoirs in the NE Netherlands. A complex interplay of wrench
tectonics was recognised to have been active from Carboniferous times till present. Two near-parallel major wrench fault systems have been recognised in the subsurface of the NE Netherlands. Wrench tectonic signatures, largely as a result of dominant NW-SE oriented wrenching are ubiquitous, both in cross-sections and map-view: en-echelon synthetic Riedel faults, antithetic Riedels, strike-slip displacements of up to several hundreds of metres and pull-apart basins of up to 2 kms wide, significant reverse faults and folds and positive as well as negative flower structures with deeply rooted, steep master faults.

These features are in full reconciliation with the wrenching criteria as proposed by Harding 1990. The features are the result of near-continuous largely N-S compression and related E-W extension. Harding is considered, despite his excellent and revealing paper, to have been over-critical on details regarding the previous identification by a number of authors of wrench tectonics in the Netherlands. On the other hand, the quality of seismic visualisation techniques has developed explosively over the past two decades, enabling detection of details as well as large-scale regional patterns.

It proved that fractures are ubiquitous in Zechstein carbonate reservoirs of the NE Netherlands. The orientation of as much as 6000 fractures measured from cores and Borehole Image logs is fully in reconciliation with the wrench tectonic signatures related to dominant NW-SE wrenching through time. Signatures from seismic attribute maps support the orientation of wrench tectonic deformational features. Borehole-break-outs as detected from Borehole Image logs confirm significant largely N-S oriented present-day horizontal stress anisotropy. This fact is actively being applied in the design of hydraulic fracturing of tight reservoirs.

Palaeo-wrench-tectonic deformation features explain the depositional patterns, distribution and orientation of Carboniferous fluvial deposits, Rotliegend aeolian-fluvial deposits and Zechstein 2 carbonate deposits, as well as the development of off-platform carbonate build-ups. Wrench related cataclastic strike-slip faults as well as major open fracture systems explain the anomalous productivity and connectivity behaviour of Carboniferous, Rotliegend and Zechstein reservoirs. These deformational features are being incorporated in 3D modelling and simulation studies in order to obtain a match with the production performance of reservoirs and to predict reservoir behaviour.
In Chapters 2, 3 and 4, recently discovered, immature and smaller Rotliegend Sandstone reservoirs are analysed, NAM's major asset, whereas aspects of the mature Zechstein and Carboniferous reservoirs are covered in Chapters 5 and 6 respectively.

In Chapter 2, the various reservoir-geological conditions are described that contribute to the anomalously poor performance of a number of small offshore Rotliegend Sandstone reservoirs. Significant areal variation in reservoir quality as a result of sedimentary processes, probably influenced by syn-sedimentary faulting, is one aspect of unexpectedly problematic reservoir behaviour. Strong differential depletion of scattered, thin and highly permeable aeolian sand layers is described, together with insufficient (cross)flow from poor quality sand packages, due to varying amounts of diagenetic clay minerals and laterally extensive shale barriers reducing and preventing the vertical cross-flow of gas.

In addition, the feature of compartmentalisation by in-field cataclastic, sub-seismic strike-slip faults resulting from wrench tectonics is introduced, one of the major causes of the poor productivity and connectivity. It is shown that formation impairment by drilling fluids and wellbore isolation due to cement filled washouts may also contribute to the poor performance of wells. Two reservoir-geological/petroleum-engineering field examples are presented and methods are described to identify, predict and remedy the problems to reduce the business risk associated with field developments.

In Chapter 3 the problematic development aspects of the offshore K15-FG Rotliegend Slochteren Sandstone reservoir are described. For the first time in NAM's history, the feature of compartmentalisation by sub-seismic strike-slip faults was identified from signatures from borehole image logs, combined with core data and lineations on seismic azimuth maps and these were matched with production performance. This then novel technique has been successfully applied in successive years to explain the anomalous behaviour of several individual reservoirs.

In Chapter 4 a case history is provided of the offshore L13-FE Rotliegend Sandstone reservoir. The first development well in this strongly layered Slochteren Sandstone reservoir showed extremely poor productivity and connectivity and proved in hindsight to be located in a small fault compartment.
The chapter provides details on the planning, production-technology and drilling-engineering aspects, execution and results of a sub-horizontal sidetrack. It is illustrated that challenging such complex, layered, labyrinthine, and fault-compartmentalised reservoirs by a fully integrated, multi-disciplinary approach is essential and that slim-hole sub-horizontal drilling together with the application of completion by a slotted liner may be cost-effective and successful. Furthermore, the application of 3D computer modelling is described, together with the use of outcrop analogue data sets and geochemical techniques for optimisation of development planning.

In Chapter 5 the re-juvenation in development of the mature Zechstein 2 platform carbonate reservoirs in SE Drenthe is presented. Economic development of these overall tight reservoirs is fully dependent on wells encountering major open fracture systems. In Chapter 2 indications of wrench tectonics in the Dutch offshore area had already been introduced. Analysis by the author of the regional structural deformation history of the onshore NE Netherlands area has revealed that a complex interplay of wrench tectonics has been active from the Carboniferous to the present and that wrench tectonic deformation features are ubiquitous.

Analysis of some 6000 fractures from cores and borehole image logs shows that their orientation is fully in reconciliation with the synthetic Riedel, antithetic Riedel and extensional fractures related to wrench tectonics. Furthermore, it proved that some 20% of the fractures are open and these are oriented largely N-S, largely parallel to the present-day maximum horizontal stress in the NE Netherlands.

A novel model is presented, predicting the spacing of the open major fracture systems, based on wrench tectonic signatures in the subsurface and supported by a number of outcrop analogues. The model has been validated by the results of eight recently drilled, E-W oriented horizontal wells, intersecting open ‘mega’ fractures and showing up to 300-fold productivity improvements. A number of tight reservoirs which had previously been qualified as non-reservoir and/or non-producible may have now become candidates for development. Furthermore, the possible presence of off-platform carbonate build-ups, triggered by syn-sedimentary wrench faulting within the Zechstein basin, is analysed and this may lead to appraisal of additional reserves.
In Chapter 6 new concepts regarding the architecture and possible re-development of the mature Carboniferous reservoirs is presented. Sequences of highly productive, laterally very extensive, multi-storey braided channel sand complexes have been identified, overlain by poorly productive, discontinuous meandering channel deposits, representing labyrinthine reservoirs. Syn-sedimentary faulting is identified as well as sub-seismic faulting, which explains the occasional poor connectivity of the major braided channel reservoirs.

Three-dimensional computer modelling is described, together with the application of geometrical data sets from outcrop analogues. Furthermore, reservoir properties obtained from inversion of seismic data are being used in 3D modelling for calibration and validation. A field case is presented which acts as a pilot for further development of a number of Carboniferous reservoirs.
CHAPTER 2

Character and performance of small Rotliegend gas reservoirs, Central Offshore Netherlands *

Abstract

Gas production in the central offshore of the Netherlands is mainly from Upper Rotliegend Slochteren Sandstone reservoirs consisting of aeolian-fluvial deposits. A number of small gas reservoirs show large variations in well productivity and frequently disappointing reservoir connectivity. These fields therefore deviate from the predictable characteristics of the large fields. The small fields are located in areas having poorer reservoir development than those comprising the large fields. Palaeo-topography induced by syn-sedimentary faulting may well explain the lateral variations in reservoir development. When stratigraphic, diagentic and fault compartmentalisation effects are added, the result is severely reduced reservoir connectivity in small fields.

This paper presents the various geological conditions that are thought to contribute to the poor performance of small fields. It also provides two field examples and gives an indication of the methods used to identify, predict and remedy these problems, in order to reduce the business risk associated with field developments.

A number of partly interdependent, contributory geological conditions have been identified: 1) Regional sedimentary compartments: large areal variations in the number and distribution of prolific, frequently thin, high porosity-permeability sands, interbedded in zones of significantly poorer quality sands, 2) Stratigraphic compartments: insufficient vertical permeability/cross-flow potential from poor quality sands into prolific sands, due to presence of shale barriers and diagentic clay minerals, 3) Fault compartments: the presence of mylonitised strike-slip faults, 4) Wellbore impairment and isolation due to interactions of authigenic clay minerals with drilling and/or completion fluids, and due to occurrence of cement filled wash-outs.

The discovery well often provides the only opportunity to gather information on which reservoir performance predictions are based. Extensive production testing and production logging, followed by critical well test analysis, has been applied to enhance the detection of depletion effects. Three-
dimensional reservoir-geological modelling, followed by reservoir engineering simulation studies are being carried out. Sub-horizontal drilling techniques, together with improved selection of drilling fluids and hydraulic fracturing are currently being applied successfully as remedial activities.


2.1 Introduction

Production in the offshore NAM operated K and L blocks (Fig.2) is mainly from structurally trapped Lower Permian, Upper Rotliegend, Upper Slochteren Sandstone reservoirs. As the larger fields have now been developed, exploration and development have focused on smaller structures, making use of the existing infrastructure where possible, to enhance the economic attractiveness. For the larger fields (GIIP: 10 - 50 x 10⁹ m³) the observed reservoir drive mechanism is depletion without aquifer support. This tank-like behaviour has allowed for generally reliable production forecasting. From the late 1980’s onwards, the development of smaller structures has been actively pursued by means of mini-satellite platforms and by extended-reach drilling from existing offshore facilities (Fig.3). Time between field discovery and first production has in the most recent case been reduced to as little as 2 years, as achieved in 1990 with K15-FG (Fig.2).

Production test results of a number of small field discovery wells in the central offshore show production variations of over two orders of magnitude (0.02 x 10⁶ to 4.4 x 10⁶ m³/day at 50 bar drawdown). Well productivities are apparently largely determined by the presence of high porosity-permeability sand layers. During the subsequent production period, the behaviour of the smaller reservoirs has been observed to be different from that of the larger fields. Comparison of calculated volumetric GIIPs with the connected GIIPs as established from material balance calculations, shows that for most of the fields with a volumetric GIIP less than some 10 x 10⁹ mrd m³, only a small part of the gas is likely to be connected (Fig.4) to the limited number of wells which can be economically afforded to develop these accumulations.

The small fields are located in areas having poorer reservoir development than those comprising the large fields and when stratigraphic, diagenetic and fault
compartmentalisation effects are added, the result is severely reduced reservoir connectivity in small fields. The combination of low gas volumes in place, with the associated reservoir connectivity risk, is the main cause for these field developments being frequently only marginally economic. Three-dimensional reservoir-geological modelling is being carried out, to be followed by reservoir engineering simulation studies. These are expected to improve the prediction of long term field behaviour, thereby reducing the business risk associated with field development.

The Upper Rotliegend in the area is subdivided from top to bottom into the following units (Fig.3), of which an abbreviated nomenclature will be largely used in the text and figures:

- Ten Boer Claystone : ROCLT
- Upper Slochteren Sandstone : ROSLU
- Ameland Claystone : ROCLA
- Lower Slochteren Sandstone : ROSLL

2.2 RESERVOIR-GEOLoGICAL ASPECTS

2.2.1 Depositional model and reservoir properties

The Upper Rotliegend Slochteren Sandstone in the K and L area has been deposited at the southern margin of the NW-European Permian Basin. An extensive alluvial wedge (bajada) developed under desert conditions, with sediments derived from a source area located to the south, the Variscan London-Brabant Massif. The sandy alluvial wedge comprises a number of alternating facies (Fig.5) and gradually shales-out to the north into a sabkha depositional environment in the northern half of the K and L blocks (Glennie et al. 1978, and Oele et al. 1981).

Core data from the K and L area show a number of alternating lithofacies types. A) Waterlaid deposits: 1) mudstones, deposited by a playa lake and ponds, 2) clay-rich sands and silts from damp and wet sand- and mudflats (Fig.4), and 3) sands, silts and conglomerates, deposited by non-channelled sheetfloods and by braided fluvial (wadi) channels. B) Wind-reworked deposits: dry sandflats, aeolian sheet sands and aeolian dune sands (Fig.5).

The Upper Slochteren Sandstone shows an overall wetting-upwards trend, consisting of thinner, stacked drying- and wetting-upwards cycles. Aeolian sands comprise the overall better reservoir quality (Fig.6), when compared to waterlaid
sands (Nagtegaal 1979). The inflow characteristics of wells as indicated by production logs (PLTs) show that the gas-flow from the Upper Slochteren Sandstone (ROSLU) is mainly from aeolian sands with porosities in excess of 15% (Fig.7).

The distribution of these highly productive sands in the ROSLU has been mapped across the K15 / L13 area of the Central Dutch offshore. In this area the major productivity and connectivity problems occur. Three areas stand out as having a clearly higher percentage of prolific, high porosity-permeability sands (Fig.8A). These areas probably reflect the presence of topographically higher areas during deposition with a relatively deep palaeo-groundwater table, where aeolian sand seas (ergs) developed. Dipmeter logs allow recognition of the thicker aeolian sands (Fig.9). The aeolian foresets predominantly dip to the west and southwest, reflecting the palaeo-wind orientation. Significant permeability contrasts exist in these deposits due to an alternation of partly cemented, finer-grained laminae and coarser-grained slipface sandlayers (Van Veen 1975, Nagtegaal 1979, Weber 1987). Therefore better horizontal permeabilities exist largely parallel to the aeolian foresets.

These more prolific areas alternate with N-S trending zones with markedly lower percentages of prolific sands (i.e. larger proportions of waterlaid sands: regional sedimentological compartments). This is in line with the palaeo-depositional pattern of sheetfloods and wadi-channels, trending northward from the London-Bradant Massif towards the basin centre (Fig.8, insert; Glennie, Mudd and Nagtegaal 1978, Oele, Hol and Tiemens 1981).

Furthermore, areas exist, e.g. the southeastern and northeastern part of the L13 block, where only relatively thin prolific sands are present, which frequently are too thin (as thin as 25 cm) to be detected from dipmeter logs. Such sands appear to have only a limited lateral extent and have a rather scattered occurrence throughout the reservoirs (comparable to 'labyrinth-type' reservoirs, Weber and van Geuns 1989).

Net/gross ratios show a similar distribution pattern (Fig.8B). A high proportion of shales occurs across the areas where wadi channels and sheetfloods were dominant and where temporary desert lakes and ponds were created. Correlations show the frequently lateral extensive character of these shales, thereby furthermore reducing the overall vertical permeability and cross-flow potential (stratigraphic compartments) within reservoirs located in these areas. In addition, a general
northward increase in abundance of impermeable layers is also evident (sabkha and
playa lake margin deposits, Figs.5 and 8B).

Recent exploration and development wells confirm the mapped trends. It is
significant that the smaller fields are located in areas of poorer reservoir
development, i.e. limited amounts of prolific, high porosity-permeability sands with
a frequently scattered nature, together with a relatively large amount of continuous
shale layers.
Palaeo-topography induced by N-S trending syn-depositional faulting may well
explain the lateral variation in reservoir development in the area, i.e. the palaeo-
high areas being more exposed to aeolian activity, whereas the palaeo-low areas are
more exposed to influence of the playa lake conditions towards the north.

2.2.2 Structural architecture

The structural architecture of the K15 / L13 area is characterised by the effects of
complex wrench tectonics (Ziegler 1975). This is indicated by: 1) an overall NW-
SE oriented anastomosing, braided fault pattern, characteristic of transcurrent fault
zones (Fig.10), 2) some dextral displacement of NE-SW trending faults in a SE
direction along the major faults and 3) occurrence of reverse faults.

Stress field rotation of up to 90 degrees during deformation can be deduced from
the difference in strike of reverse faults: 1) NNW-SSE trending reverse faults (e.g.
in the L13-FC field, Fig.10), probably result from inversion of the Broad Fourteens
Basin (Jurassic-Cretaceous), 2) NE-SW trending reverse faults (e.g. in the L13-FD
field, Fig.10), probably result from Alpine orogenic compression.

Synthetic and antithetic strike-slip faults, associated with wrench tectonics, may
have only minor vertical offsets, and therefore recognition on seismic sections is
often difficult. Nevertheless, lineations on seismic attribute maps (e.g. Azidip
displays) may provide evidence for the existence of such features (Fig.11).

Additional evidence for the presence of strike-slip faults and reverse faults is
provided by: 1) shear fracture trends from CBIL logs, 2) structural signatures from
conventional dipmeter logs (Fig.12), 3) minor fault picks from log correlations, and
4) internal reservoir boundaries interpreted from well test analyses. This dextral
wrench model matches the observed configuration in a number of fields (e.g. L13-
FD, Fig.11).

Mylonitisation due to intense cataclasis along strike-slip faults may cause
sealing potential of such faults. Similar to juxtaposition due to normal faults, this
may (especially in thinly bedded reservoirs) cause disruption of the thin prolific layers, even though the fault throws are limited. In well K15-FG-102 the core data and an interpretation of the CBIL log showed that mylonitised subvertical fractures (associated with a small reverse fault cutting the wellbore) are abundant. The transmissibility across such fractures is typically very poor. In combination with poor vertical connectivity due to areally continuous shale intercalations, compartmentalisation by cataclastic faults may result in poor connectivity of the gas in place to the wells. This combination is the main cause of poor drainage of these small reservoirs (fault sealing by clay smear is not considered to be significant due to the relatively thin nature of the scattered shale layers).

### 2.2.3 Diagenesis

The diagenetic history of the K15 / L13 area is characterised by near-continuous burial (Fig.13), interrupted by relatively short periods of uplift. During burial, detrital feldspar grains were transformed into kaolinite. Kaolinite is the most abundant clay mineral type in the ROSLU sands (as high as 6% of bulk rock volume). Locally, e.g. in the SE part of the L13 block (Figs.14A,B), kaolinite was transformed into fibrous illite, and smectite (mixed-layer clay with swelling potential).

The generation of these clay minerals in the SE part of the L13 area is not related to previous anomalous deep burial as in other areas (Fig.13, the K17 block is located to the southwest of K15). In the southeastern L13 area the illitisation has been interpreted as being related to variable heat and fluid flow (Rossel 1982). Most likely, anomalously high temperatures were introduced by movements of the underlying basement wrench faults in the L13 east area (a feature known from reservoirs in the Central Michigan Basin, USA, Girard and Barnes 1995), together with the local absence of Zechstein salt packages (salt being conductive to heat).

The high content of authigenic clay-minerals in the sediments has drastically reduced permeabilities (Fig.6), thereby minimising gas cross-flow potential into the depleted, prolific sands (Fig.7). Together with the depositional and structural factors mentioned previously, these have a detrimental effect on reservoir productivity and connectivity in the area.
2.2.4 Mechanical impairment

In addition to geological controls on poor productivity, drilling, stimulation and completion practices may also have contributed to poor productivities. Additionally to the presence of illite and illite/smectite in reservoirs of the southeastern L13 area, a relatively high content of authigenic, pore-bridging iron-chlorite clay-minerals also occurs (up to 20% of the total clay-mineral fraction). The presence of iron-chlorites may create potential problems during matrix-stimulation with mud-acid, since these clay minerals are prone to form iron-hydroxide gels when acid compositions are not carefully designed.

In areas with relatively low N/G, consolidated shales and more severely cemented sand intervals alternate with zones of friable, highly permeable sands. Therefore, considerable borehole wash-outs may occur (Fig.15) when drilling hydraulics is not carefully controlled. It is possible that perforations across these potentially prolific sands do not extend beyond the thick cement, isolating these zones, and hydraulic fracturing may be necessary.

In recent years the Slochteren Sandstone reservoirs were drilled routinely with oil-based mud, a change from the previously used water-based mud. This was done to ensure borehole stability (avoid swelling of shales and hence to reduce drilling problems) and to minimise formation impairment. However, well productivity is in some cases adversely affected, resulting in high skins in the vicinity of the wellbore (e.g. Fig.16). Drilling fluid impairment research is being carried out to improve the delicate balance between formation impairment and drilling performance.

2.3 GENERAL RESERVOIR ENGINEERING ASPECTS

In all reservoirs in the central offshore Netherlands the well inflow performance is dominated by high porosity-permeability layers. In larger fields, these prolific layers are generally thicker, laterally more continuous and less separated by shales and hence they exhibit good connectivity with the rest of the reservoir. Straight-line material balance plots confirm that the full volumetric GIIP is connected to the wells. Well capacity decline is generally in good agreement with forecasts. The forecasts are based on well productivities measured in initial well tests and assume full reservoir connectivity.

In smaller fields however, the experience is quite different. Well capacities decline faster than predicted. The material balance plots indicate that the connected volumes may be far less than the volumetric GIIPs (Fig.4). The prolific layers have
only limited connectivity to the rest of the reservoir and as a result suffer from
differential depletion.

The material balance plots may curve upwards to varying degrees, indicating
increasing connected volumes with increasing depletion levels. Aquifer support is
not observed in the ROSLU. The aquifers are generally small as a result of fault
juxtaposition and seal. Repeated Formation Test (RFT) measurements on infill
wells have confirmed that there is no aquifer movement in depleted fields.

Development of small fields is critically dependent on high and sustainable well
capacities and on connecting the bulk of the volumetric GIIP to the well(s). Initial
well tests are therefore designed to maximise the opportunity to detect anomalously
rapid and/or differential depletion. However test durations are restricted due to the
high costs of production testing offshore and therefore conclusive depletion can
only be identified in more severely affected wells. Recently, the development of a
small field (L13-FH, Fig.2) was deferred after conclusive evidence of rapid and
differential pressure depletion during testing.

Three-dimensional reservoir-geological modelling studies are being carried out,
followed by reservoir-engineering simulation studies, to improve the prediction of
reservoir production performance of future field developments.

2.4 FIELD CASE 1: RESERVOIR BEHAVIOUR K15-FG FIELD

The K15-FG field (Fig.2) was discovered in 1988 by exploration well K15-12,
which was later tied-back as K15-FG-101 development well. The structure is a SW
dipping horst block, bounded to the NE and NW by major normal faults (Fig.17A).
The reservoir consists of two major blocks, ‘separated’ by a fault with minor
vertical throw.

The two blocks of the field, which both had an initial pressure of 400 bars, are
currently drained by two development wells from a mini-satellite platform. The gas
is evacuated to shore via the nearby production platform K15-FA-1. However, the
two wells K15-FG-101 and -102 showed significantly different test productivities
of 2 x 10^6 m^3/d and 0.4 x 10^6 m^3/d respectively at 50 bar drawdown.

Both wells have experienced capacity decline, interpreted to be the result of poor
pressure support at the wells. Comparison of the material balance GIIP with the
volumetric GIIP shows that the two development wells connect only part of the
field volumetric GIIP (Fig.4).
To evaluate the reservoir characteristics responsible for this poor connectivity, the material balance plots and the inferred reservoir characteristics for the two blocks are discussed separately.

2.4.1 K15-FG block 1

With time, the material balance plot of well -101 indicates a slight increase in connected gas volume from 1.1 to about 1.5 x 10^9 m^3 (Fig.17B, compared to a volumetric GIIP of 5 x 10^9 m^3; P/Z = pressures corrected for non-ideal gas). It is most likely that initially only the prolific, high porosity-permeability layers are directly connected to the -101 well and that the remaining volume is trapped in the low permeability sands. The volumetric expectation contained in the prolific layers alone is 1.4 x 10^9 m^3, close to the material balance volume. The curvature of the P/Z plot of well -101 in Figure 17B probably indicates increasing flow from the poorer permeability sands and/or seal failure of minor faults in the vicinity of the well. The curvature could reflect aquifer activity, however, as mentioned previously, no aquifer movement has been observed so far in the area.

The initial productivity of the discovery well was estimated at 2 x 10^6 m^3/d at 50 bar drawdown. This is relatively high for the K and L area. PLT logs show that 80% of the inflow originated from a prolific sand package at the base of the ROSLU (Fig.18, ROSLU 2), with only minor contribution from a thin sand in the middle of the ROSLU 1. No measurable contribution came from the bulk of the poorly permeable sands.

After a year of production, a multi-flow-rate PLT was run. The inflow profile confirmed that the sands of the ROSLU 2 were still dominating flow into the wellbore (ca. 65%), but in addition, some of the less permeable zones of the ROSLU 1 had started to contribute about (still only) 10% of total inflow.

It was observed from the multi-rate PLT that the gas flow rate from the less permeable zones was insensitive to variations in the drawdown pressure. This indicates that the less permeable layers were relatively undepleted, being fully consistent with the low production rates observed from the less permeable layers.

The multi-rate PLT confirmed the ability of the reservoir to sustain pressure differentials between layers. In this survey the layer pressures were estimated to range from 194 bar to 400 bar between the highly and poorly permeable layers respectively.
2.4.2 K15-FG block 2

The material balance plot of well -102 indicates a connected volume of 0.8 x 10^9 m^3 (Fig.17B, compared to a volumetric GIIP of 3 x 10^9 m^3). It is most likely that only the prolific layers are accessed by the -102 well, and that the remaining volume is trapped in the low permeability zones. Similar as for block 1, the mapped volumes contained solely in the highly permeable layers of block 2 are in reconciliation with the connected volumes estimated from material balance calculations.

Logs of well K15-FG-102 show that the ROSLU 1 contains more prolific sands than in well -101 (Fig.18), whereas the ROSLU 2 has a more layered character than in well -101. The RFT pressure profile of well -102 shows pressure differentials of up to 10 bars between the ROSLU 1 and -2 (Fig.19). This is most likely caused by the pressure sink in block 1 due to production from well -101, extending laterally across the prolific layers. The fault separating blocks 1 and 2 (in line with the antithetic strike-slip trend in the area) appears therefore to have become transmissible (the highly permeable ROSLU 2 in block 1 had already been depleted by 200 bars).

On test, well K15-FG-102 showed a productivity at 50 bar draw down of only 0.4 x 10^6 m^3/d, compared to 2.0 x 10^6 m^3/d from K15-FG-101. The inflow profile was much smoother than in well -101, with contributing intervals more evenly spaced (Fig.18).

In well K15-FG-102 the core data showed that mylonitised and cemented, sub-vertical shear fractures are present in the reservoir. Transmissibility across such cemented fractures is typically very poor. Furthermore, the test analysis of well -102 showed that a no-flow boundary is present approximately 35m away from the wellbore. These facts may well explain the poor productivity of the well.

2.5 FIELD CASE 2: RESERVOIR BEHAVIOUR L13-FD BLOCK

The L13-FD block (Fig.2) was discovered in 1985 by well L13-7, which was later tied-back as L13-FD-101C development well. The structure consists of a SW dipping horst block, bounded by faults to the NE, NW and SE (Fig.20). The reservoir sands are moderately illitic (Fig.14).

The RFT profile (Fig.20) indicated that gas accumulations in the Upper- and Lower Slochteren Sandstone (ROSLU and ROSLL) are effectively separated by the
Ameland Claystone. The pressure regime in the ROSLU was in line with the adjacent L13-FC block (Fig.10), which has the same GWC and gas composition.

The L13-FD block is currently drained by two wells from a mini-satellite platform and the gas is evacuated via the nearby L13-FC-1 production platform. The second development well L13-FD-102 (Fig.20) was also drilled crestally to enable drainage of the ROSLL, and to accelerate production from the ROSLU.

In the first year of production, the wells experienced a significant capacity decline. After two years the field’s production capacity had declined further. The ROSLL in well -102 had watered-out and was shut-off. The material balance plot indicates an emerging re-pressurisation trend (Fig.21), but the connected volume was estimated to be only $1.6 \times 10^9$ m$^3$ (compared to a volumetric GIIP of $3.8 \times 10^9$ m$^3$).

Poor vertical communication is considered to be the main cause for the block’s disappointing behaviour. It is most likely that only the highly permeable layers are connected to the wells. The gas volumes in these layers can be reconciled with the initially connected volumes. The remaining gas is trapped in the poorly permeable, moderately illitic sands. However, the field seems to contain (possibly mylonitised) strike-slip faults (Fig.11) and a no-flow boundary was observed in the ROSLL of well -101 during test.

It is possible that, as pressure drops further during depletion, the additional gas trapped in the low permeable layers will start to flow into the more permeable layers within the reservoir. This will be dependent on whether shale baffles extend through the package to form a complete seal. Furthermore, additional gas flow may be caused by failure of initially sealing strike-slip faults (a feature observed in other reservoirs, e.g. K15-FG). There is most probably limited connectivity with the adjacent L13-FC block. About 10 bars depletion was noted in well L13-FD-102 whilst the L13-FC block had depleted to 200 bars by that time, indicating seal failure of the separating fault between the blocks.

### 2.6 Remedial activities

To remedy the connectivity problems in current developments, sub-horizontal wells have been drilled and more are planned, to connect different fault compartments, while still achieving full penetration of the gas column. Furthermore, the probability of intercepting a larger number of prolific sands may be increased by sub-horizontal drilling, as proven in a recent well L13-FE-102 Sidetrack (Chapter 4).

Hydraulic fracturing in sub-horizontal wells, together with improved selection of drilling fluids, is planned for in illitic and layered reservoirs with strong
permeability contrasts. Hydraulic fracturing also overcomes wellbore impairment and near-wellbore flow barriers/faults, which have been identified in conventional wells (e.g. K15-FG field, Chapter 3).
CHAPTER 3

Borehole Image logs: vital for evaluating disappointing well and reservoir performance, K15-FG field, Central Offshore Netherlands *

Abstract

The first two development wells of the K15-FG Rotliegend gas reservoir showed a large variation in productivity and sharply declining flow rates. Material balance data indicated only 30% of the field’s expected Gas Initially In Place (GIIP) to be connected to the wells.

A Circumferential Borehole Imaging Log (CBIL) was run in the second development well. The CBIL enabled identification of small-scale reservoir heterogeneity and thin, otherwise undetected highly productive aeolian layers. The log analysis also revealed the presence of a conjugate set of shear fractures, confirmed by cores. Furthermore, small scale, sub-seismic resolution reverse faults were detected intersecting the wellpath, as well as anomalous structural dips around the well, indicating fault drag. The presence of near-wellbore reverse faults and sub-vertical shear fractures with cataclastic fill, restricting horizontal inflow, explains the disappointing production rates of the second well.

Moreover, continuous borehole breakouts were observed from the log, indicating present-day stress anisotropy. The CBIL data in combination with lineations observed on seismic attribute maps contribute to a concept of dextral wrenching across the field, with related reverse faulting and strike-slip faults or shear zones. Such a configuration of partly and completely sealing faults is a major cause of the significantly different productivities and the overall poor reservoir connectivity as confirmed by pressure behaviour.

The CBIL is an effective tool for evaluating both structural and depositional reservoir heterogeneity. The resulting interpretations created scope for optimisation of recovery by resolving the causes of anomalous well behaviour and field architecture. Pressure analysis of a recently drilled third development well has once more confirmed the presence and sealing character of strike-slip faults within the field.
3.1 Introduction

The K15-FG field offshore Netherlands (Fig.22) consists of a tilted horst block, largely bounded by normal faults. Gas is trapped in the Upper Rotliegend aeolian-fluvial Slochteren Sandstone of which the strongly layered Upper Slochteren Sandstone (ROSLU, Fig.23) is the main gas-producing interval. The overlying anhydritic Ten Boer Claystone (ROCLT) and the underlying Ameland Claystone (ROCLA) members (sabkha and lacustrine facies) are waste zones. Thick Zechstein salts provide both top and lateral seal (Fig.23). For a detailed description of the history of anomalous reservoir behaviour reference is made to Chapter 2.4.

A CBIL (Circumferential Borehole Imaging Log, Atlas Wireline Services 1991) was run in oil-based mud in the second well (CBIL: In Greek mythology Sibyl was the name for a woman whom inspired by the god Apollo prophecised in ecstasy”). The CBIL was run to obtain a more detailed picture of the reservoir architecture (stratigraphic heterogeneity, sedimentary structures, detection of possible fractures and stress-field anisotropy) for 3-D computer modelling and simulation and hence for the planning of possible future infill wells and hydraulic fracturing design.

3.2 CBIL data acquisition and analysis

The CBIL uses acoustic transducers, operating in a pulse-echo mode, to scan the entire circumference of the borehole wall. The transducers are hemispherically focused to optimise the image resolution and rotate six times/second, acquiring 250 samples/revolution. The CBIL images are derived from reflections measured directly from the borehole wall.

Changes in amplitude of the obtained signal reflect variations in rock property, resulting in the identification of sedimentary structures and textural variations. Furthermore, the full borehole wall coverage of the CBIL log offers
a particular advantage in the description and analysis of structural features in the wellbore.

The images are analysed on PC-based workstations. The displays represent cylindrical images, which are 'cut along a reference line (usually true north of the borehole) and unrolled' (Fig.24). The true dip of planar geological features (corrected for borehole deviation and azimuth) is calculated either automatically or manually. CBIL processing generates a large data set that needs careful interpretation and calibration with core data and 3D-seismic data.

### 3.3 Lithological analysis

The resolution of thin beds by the CBIL was excellent. Centimetre to decimetre thin shale intercalations, partly to fully cemented streaks and layers, alternating with porous sands, were detected from the images (Fig.25) and these were confirmed by core data. Such thin beds and small-scale heterogeneities are beyond the resolution of conventional logs. Detailed knowledge of the internal heterogeneity, especially in the waterlaid sands, is of importance to better quantify the vertical permeability anisotropy in this rock-type.

Thin aeolian cross-bedded sands (characterised by porosities in excess of 15%) of only 25-50 centimetre thickness were identified from the images (calibrated by core data), showing dips towards the southwest, indicative of the palaeowind direction (Fig.26). Again such thin beds are mostly beyond the resolution of porosity logs. Details about the distribution and character of such sands enables reconstruction of the 3-dimensional arrangement of such sands (Luthi & Banavar 1988). Outcrop studies provide further information about the dimensions of such deposits, helping to provide an improved calibration of well productivities (Chapter 4.7).

Small-scale internal heterogeneity within these aeolian deposits appears to lie also within the resolution of the CBIL. Alternations of more porous, coarser-grained slipface (grainflow) beds with finer-grained, partly cemented (grainfall) laminae have been recognised, as well as cemented toe sets of small dunes at the interface with the interdune sabkha (Fig.26). Unfortunately, due to poor log quality as a result of technical problems and poor hole condition across part of a cored section, details from the thicker sequence of aeolian
sands in the ROSLU 2 member (Fig.18) could not be resolved by the CBIL (Fig.9). Recommended methods like reducing the correlation interval and step distance in the analyses (Hoeker et al. 1990) did not improve the resolution. Furthermore, the acoustic impedance contrasts between the foreset laminae in these more massive sands may be too small to be accurately detected.

3.4 Dip analysis

The depth contour map of the K15-FG field indicates structural dips in the area of well K15-FG-102 of around 5-10° to the southwest (Fig.22). An initial CBIL bedding dip analysis showed too much scatter in dip-azimuth to accurately calibrate the mapped structural dips. This scatter was interpreted to be the result of the high resolution of the tool, detecting all kind of erosional surfaces. To ensure a better structural definition, a Gamma Ray log cut-off of 45 API was applied to highlight horizontally bedded shales. Thereby the mapped structural dip was largely confirmed by the shale layers showing dips of 5-10 degrees ranging from south to southwest (Fig.25). Unexpectedly a number of anomalous northward dips were encountered, especially in the laminated and shaly ROCLT member overlying the Upper Slochteren Sandstone. These anomalous dips are interpreted to be the result of fault-drag and minor folding related to reverse faulting (discussed in a following paragraph).

3.5 Fracture analysis

The image analysis showed the presence of a conjugate fracture set comprising: 1) a large set of NE-SW striking fractures (Fig.27), dipping at angles of 50-80 degrees mainly to the southeast, and 2) a smaller set of subvertical (80 degrees) NNW-SSE striking fractures (Fig.27). The frequency of these latter fractures is probably underestimated due to the fact that they occur sub-parallel to the wellbore.

Any stress field consists of three orthogonal components (e.g. Hancock 1985): maximum principal stress (σ1), intermediate principal stress (σ2) and minimum principal stress (σ3). Steep intersection of conjugate fractures indicates steep σ2 and the conjugate set can be considered to result from the stress anisotropy between the subhorizontal (σ1 and σ3), generating synthetic (dextral) and antithetic (sinistral) strike-slip faults and fractures (Fig.28). The
orientation of the conjugate fracture set from the CBIL analysis suggests a NNE-SSW trending maximum principal stress, referred to as historical $\sigma_1$ (Fig.27).

The presence of these shear fractures has been confirmed by analysis of a spot core taken in well K15-FG-102. The fractures show predominant reverse displacement of bedding. No evidence was seen from thin sections of diagenetic alteration of the matrix surrounding the fractures (e.g. cement haloes), indicating that the fractures have not served as conduits for fluids. From thin sections it was recognised that the fractures reflect cataclastic deformation of the matrix and the fracture fill largely consists of extremely fine-grained rock flour (mylonite, Fig.29). Therefore these fracture planes are typically effective permeability barriers.

3.6 Reverse faulting

Small fault cut-outs of a total of some 10 m were identified from the logs of well K15-FG-102 (Fig.18). The larger fault at the base of the ROSLU 1 was identified from the CBIL images to cut the wellbore (Fig.30). The well test analysis of K15-FG-102 indicated the presence of a flow boundary at a distance of ca. 35 m away from the wellbore, furthermore indicative of the presence of faulting. The overall abundance of reverse shear displacements of the fractures in the core led to the interpretation of these faults as cutting the well in a reverse mode (Fig.31; throw only 5-10 m, see also Fig.18). A deviated well penetrating a reverse fault from footwall to hanging wall results in the omission of strata in the well track (Mulvany 1992).

The southward dipping events on the images in figure 30 are interpreted to represent synthetics to the main reverse fault plane (Fig.28) and these indicate an east-west strike of the main fault. Such east-west trending reverse faults indicate north-south compression (i.e. $\sigma_1$ oriented N-S). This suggests a small anti-clockwise rotation of the maximum principal stress, when compared to the historical orientation responsible for the shear fractures (Fig.27). It also indicates reversal of the two other stress components, the minimum principal stress ($\sigma_3$) being in a vertical position during reverse faulting.

Minor folding and fault-drift associated with the reverse faulting explains observed anomalous northward structural dips (Fig.31). The previously mentioned conjugate fracture set in well K15-FG-102 is interpreted not to be
the result of folding, since folding and fault-drag in this case are only minor. Furthermore, our fractures show frequent reverse offsets, which is an uncommon feature in fracturing associated with folding (Stearns and Friedman 1972).

3.7 Borehole breakouts

Significant, uni-directional borehole breakouts were identified by the CBIL across a continuous interval of ca. 60m (Fig.32). Significant anisotropy between the horizontal stress components $\sigma_1$ and $\sigma_3$ may create rock-spalling and shear failure in the direction of $\sigma_3$, resulting in borehole break-outs (Mastin 1988), i.e. ellipsoidal elongation of the borehole (Fig.28). The borehole breakouts detected by the CBIL in well K15-FG-102 are oriented WSW-ENE (Fig.33). This indicates present-day maximum principal stress oriented NNW-SSE, at right angle to the breakouts. This suggests a renewed small anti-clockwise rotation of the maximum stress, when compared to the previous orientations (NNE-SSW for the shear fractures, Fig.27 and N-S for the reverse faults).

Borehole deviation may have a significant effect on breakout orientation (Mastin 1988). However, the deviation of well K15-FG-102 (ca. 20 degrees) still warrants the reliability of the breakout analysis and the conclusion of an overall, relatively minor stress field rotation of ca. 30 degrees. Stress field rotation of even up to 90 degrees has been identified from orientations of reverse faults in the neighbouring L13 block (Chapter 2). The present-day stress field as analysed from well K15-FG-102 is in line with the regional stress regime across NW-Europe (e.g. Klein & Barr 1986, Gruenthal and Stromeyer 1994).

As a result of the stress field rotation, the present-day maximum principal stress became near-parallel to the historical, NNW-SSE striking, subvertical fracture set (Fig.27). Consequently, this fracture set appears to have turned into minor dilational shear fractures as seen in cores (shear with subordinate dilation, Hancock 1985). However, no evidence for the presence of truly open fractures was found in cores or from the CBIL images. Nevertheless, evidence for the presence of open fractures, contributing significantly to productivities, has been recognised from a number of Rotliegend fields in the area (PLT data, cycle skips on sonic logs and losses while drilling, Chapter 2.2.4).
3.8 Structural architecture

The overall structural style in the area is dominated by ubiquitous NW-SE trending normal faults with super-imposed smaller NE-SW trending faults. Dextral wrenching along NW-SE trending Variscan basement faults in the Central Offshore area has been previously reported (e.g. Ziegler 1978).

However, major fingerprints of true wrenching (like e.g. pull-apart basins, flower structures, Harding 1990) are not recognised in the area. Nevertheless, in a number of fields the effects of super-imposed dextral wrenching and associated deformation features have been recognised, such as reverse faulting and strike-slip faults or shear zones (e.g. Figs.10 and 11).

The orientation of the stress field as indicated by the CBIL analysis of well K15-FG-102 field is in accordance with dextral strike-slip interpretation along the NE boundary fault of the field. From a seismic azidip map of the field an E-W trending, northward dipping lineation was recognised just south of well K15-FG-102, which is in line with the interpreted reverse fault and fault-drag zone (Fig.34). A number of additional lineations on the azidip map are in line with the strike of deformation features (synthetic and antithetic shear), associated with the stress anisotropy resulting from dextral wrenching (e.g. Biddle & Christie-Blick 1985). These lineations are interpreted to represent the presence of strike-slip faults or shear zones. Such faults are generally beyond the resolution of conventional seismic due to the very limited vertical throw.

3.9 Impact on reservoir behaviour

In combination with stratigraphic compartmentalisation, the presence of strike-slip faults or shear zones is interpreted to be a major cause of the relatively poor reservoir connectivity in the area of the K15-FG wells. Such shear zones at least restrict repressurisation of the wellbores, which may be time and pressure dependent. However, obviously completely sealing strike-slip faults have been recognised from well behaviour in the L13-FE field in the area (Chapter 4).

The NE-SW striking fault separating wells K15-FG-101 and -102 (Figs.22 and 34) shows some normal displacement on seismic sections. However, this fault has most likely been reactivated by antithetic strike-slip, because only minor pressure communication across this fault was recorded from Repeat Formation
Tester (RFT) measurements in well K15-FG-102 (10 bar depletion, compared to depletion of ca. 200 bars in well -101).

The strike of the aeolian foresets in the K15-FG area is NW-SE to NNW-SSE (Fig.26) and therefore better horizontal permeabilities are expected in this direction (Chapter 2.2.1). The reverse faults to the south of well K15-FG-102 and the antithetic shear fractures and strike-slip faults are near-perpendicular to the strike of the aeolian foresets, thus severely restricting horizontal inflow. This explains the disappointing production rates of well K15-FG-102 when compared to K15-FG-101.

An additional development well K15-FG-103 has been drilled to the southwest of well K15-FG-101 (Fig.34). The well revealed a pressure depletion of only 20 bars (expected depletion 130 bars), which once more confirmed the presence and sealing character of strike-slip faults within the field.
CHAPTER 4

Sub-horizontal drilling: remedy for underperforming Rotliegend gasfields, L13 block, Central Offshore Netherlands*

Abstract

The first development well in the L13-FE gasfield showed a rapid production decline. Material balance data indicated less than 10% of the expected volumetric reserves to be connected. This poor connectivity is thought to the result of compartmentalisation by sealing strike-slip faults, as indicated by faint lineations observed on seismic attribute maps. The presence of only a limited number of scattered, stratigraphically isolated, prolific layers within an overall rather tight and layered reservoir, resulted in a poor overall vertical permeability, which also contributed to the disappointing well performance.

The vertical well was subsequently sidetracked sub-horizontally with the aim to connect a larger number of the scattered prolific sands, different fault-compartments and possible open fracture systems. Graded rocksalt drilling mud was used in order to minimise formation impairment. During drilling of the sub-horizontal section numerous problems were encountered due to mechanical failures and the heterogeneous, layered nature of the reservoir.

A significant number of prolific, scattered sand layers were encountered and the presence of a small scissor-type fault was recognised from log correlations. Considering that only some 60% of the well could be completed due to mechanical problems, the well is producing at acceptable rates and shows overall good connectivity. The attempt to challenge such a geologically complex, layered reservoir by slim-hole, sub-horizontal drilling, has been cost-effective and successful.

4.1 Introduction

The L13-FE field was discovered in 1986 by exploration well L13-8 (Fig.35). The field consists of an apparently undisturbed, NW-SE trending, tilted fault block, which is dip-closed to the SW and fault-closed to the NE and NW. An expected volumetric Gas Initially In Place (GIIP) of ca. $4.6 \times 10^9$ m$^3$ is trapped in the Permian Rotliegend Upper Slechteren Sandstone reservoir.

Following the discovery in 1990 of the neighbouring L13-FG field, situated some 2 km to the east, simultaneous development of both fields was planned. The L13-FG field was developed by means of an extended-reach well (L13-FE-101) from a mini-satellite platform installed on the L13-FE field and two crestal wells were drilled to develop the L13-FE field. The first well L13-FE-102 was drilled ca. 250 m north of the abandoned L13-8 discovery well (Fig.35). However, the well showed a disappointing test rate of $0.3 \times 10^6$ m$^3$/day (compared to $1.3 \times 10^6$ m$^3$/day of well L13-8). Subsequently, rapid production decline and marked pressure depletion occurred and material balance calculations indicated less than 10% of the expected reserves to be connected (Fig.36). It is therefore doubtful whether development of this relatively remote area would have taken place when the disappointing well L13-FE-102 would have been the discovery well of the field.

From production logs (PLTs) it was evident that the direct inflow into the wellbore was largely dominated by two highly permeable, ca. 1 m thick sand layers (stratigraphically isolated between shales) in the topmost part of the reservoir (Fig.37). As such the field showed all the characteristics of suffering from the so-called "small field behaviour", which was simultaneously observed in a number of recent offshore developments (Chapter 2). The main causes for such behaviour are considered to be: 1) Significant areal variations in the amount of highly permeable, prolific layers. In the L13-FE area only minor amounts of such prolific layers occur (Fig.38, ca. 15% of gross rock), when compared to other areas like e.g. the K15 central area (ca. 50% of bulk rock). The rather unpredictable, scattered nature of such ca. 1 m thin aeolian layers reflects a 'labyrinth-type' reservoir, 2) Stratigraphic (vertical) compartmentalisation of the prolific sands due to the presence of shale barriers, restricting cross-flow inside the reservoir from poor quality sands into prolific sands and 3) Compartmentalisation (lateral) due to sub-seismic, largely sealing strike-slip faults or shear zones and small normal faults.
Shortly after production start-up of the well a seismic Azidip map became available, based on a recently acquired 3D seismic survey. This map showed N-S trending, en echelon lineations to the northwest of the well (Fig.39). The lineations have been interpreted to represent largely sealing strike-slip faults or shear zones. These are probably the result of dextral wrenching and these features have also been recognised in other fields in the area.

Such faults are beyond the resolution of conventional seismic due to the limited vertical throw and their presence can only be identified by means of detailed seismic attribute mapping. Their sealing potential is analysed from pressure behaviour of wells. Taking into account the signature of the map and the production performance, it was obvious that the well had been drilled into an isolated fault compartment.

4.2 Planning

The second development well L13-FE-103 was initially planned ca. 1 km to the northwest of well -102. Based on the anomalous well behaviour of well -102 and on the indications from the seismic Azidip map, the location of well -103 was shifted some 600 m further to the northwest, across a discontinuous normal fault (Fig.35). This was done to reduce the likelihood of fault-interference at the proposed -103 location and to create an opportunity for either re-drilling or sidetracking the underperforming -102 well towards the northwest.

Well -103 encountered top Rotliegend ca. 45 m deeper than prognosis, due to uncertainties in the pick of an overburden unconformity and thickness variations of the overlying, wedging salt caprock. A Vertical Seismic Profile (VSP) survey obtained from this well -103 confirmed the presence of fault disturbances.

Three options were considered for remedial action for the underperforming -102 well:

1) Stimulation by hydraulic fracturing. This option was ruled out due to uncertainties in fracture propagation distance and orientation (no stress-field data available) and due to technical restrictions of fracturing from a mini-satellite platform.

2) An additional well to the northwest of -102, together with maintaining the low and decreasing production rates of the existing well. Cost considerations and timing ruled out this option.

3) A sub-horizontal sidetrack of -102, towards the northwest along the almost horizontal crestal section of the field (Fig.39). This option would have the
advantage of: a) cost effectiveness (ca. 30% of the costs of a new well), b) early production and c) the possibility of connecting a larger number of prolific sands, open fractures and fault-compartment, while still penetrating the full gas column. A completely horizontal well was not considered due to the rather layered and heterogeneous character of the reservoir and the limited penetration angle it would make with the almost horizontal reservoir section along the crest of the structure.

4.3 Design

Due to a major repair job in the 13 3/8" casing of the original well L13-FE-102, the sidetrack was designed to kick-off relatively deep, out of the 9 5/8" casing (Fig.40). The main build-up section was to be delayed until confirmation was obtained about the position of the uniformly thick Zechstein 2/1 Anhydrite/Dolomite section. This was done by means of Gamma Ray- Measurement While Drilling (GR-MWD) log monitoring because of uncertainty in thickness of the overlying Zechstein 3 Anhydrite and the salt wedge, Fig.40).

The 7" liner was planned to be set at the end of the build-up section, at the top of the Upper Slochteren Sandstone. Since no further MWD logging tools (besides GR-MWD) would be available for the 5 7/8" subhorizontal hole section, pipe-conveyed logging of this section was selected. The logging was planned to include a Circumferential Borehole Imaging Log (CBIL) for fracture detection and analysis of stress-field anisotropy for possible design of hydraulic fracturing. It was decided to complete the hole with an open hole slotted liner, in order to enable possible future retrieval of the liner for hydraulic fracturing.

4.4 Performance estimation

In order to design the optimum angle for the sub-horizontal well, sensitivities on the inflow performance were analysed with respect to permeability anisotropy, slant angle and skin (based on analyses by Kuchuk and Goode 1988):

1) The productivity improvement of a sub-horizontal well, when compared to a vertical well is predominantly governed by the vertical permeability (Fig.41). Measurements of horizontal and vertical permeability from core-plugs did not show a significant anisotropy. It was recognised that effects of permeability anisotropy due to the rather extensive shale layers would be far more significant. It was evident that the layered and heterogeneous nature of the Upper Slochteren Sandstone would not be optimum for a horizontal (and even a sub-horizontal) well
and in the worst case no productivity improvement could be expected when compared to a vertical well.

2) It was calculated that the slant angle could have a significant impact on inflow performance with a major productivity increase expected from slant angles in excess of ca. 75 degrees (Fig.41).

3) Mechanical skin has a detrimental effect on (slanted) well performance (Renard & Dupuy 1991). In this respect the application of a slotted liner would carry an additional risk of poor productivity, because of the absence of perforations through the invaded zone.

Inverted Oil Emulsion Mud (IOEM) was at that time routinely applied in the offshore wells, mainly to reduce drilling problems. However, it became evident that oil-based muds could cause significant formation damage (McDonald and Buller 1992), and it was experienced that in a number of cases productivities of offshore wells were adversely affected due to use of oil-based muds (skin damage and possible effects on wettability). For this reason drilling fluid impairment tests on core samples were carried out in the laboratory with oil-based mud and graded rocksalt mud (graded rocksalt mud consist of a range of rocksalt particle sizes to block the different pore-throat sizes from mud invasion). The test results indicated that graded rocksalt mud would maintain permeabilities, almost an order of magnitude higher especially in the prolific, highly permeable sands, when compared to an oil-based mud (Fig.42). For the less permeable waterlaid sands a near-reverse effect was indicated (Fig.42). However, this was considered less relevant since these sands tend not to produce directly into the wellbore but are being depleted by cross-flow inside the reservoir.

Following these analyses it was decided to drill the sub-horizontal section at an angle of 80 degrees across ca. 600m of the reservoir. Application of graded rocksalt mud was also decided, despite poorer drilling lubrication properties when compared to oil-based mud.

Stimulation by means of a coiled-tubing acid wash (Economides, Naceur and Klem 1991) was designed in order to further reduce formation impairment. From well test pressure build-ups in the area a ratio of ca. 100 was calculated between horizontal and vertical permeability (Kh/Kv, Fig.41) and a permeability thickness product of 200 mD.m. The expected productivity at 50 bar draw down, under semi-steady state conditions (Q50 sss) was estimated to be ca. 0.8 x 10⁶ m³/day (Fig.41).
4.5 Execution

During sidetracking in the overburden, GR-MWD monitoring was applied for identification of the kick-off point for the main build-up section (top Zechstein 2/1 Anhydrite/Dolomite, Fig.40). However, correlation by means of GR-MWD was not straightforward, as no full logging suite is available during drilling. Together with poor drill-cuttings control as a consequence of turbine drilling and an unexpected, poorly developed Zechstein 3 Dolomite, significant uncertainties evolved. Apparently the Zechstein 3 and 2 Dolomite markers were being encountered 50 m deep (Fig.43), with the consequence of not being able to enter the reservoir at the required location and angle.

During the build-up phase the planned for build-up angle could not be achieved, resulting in angles exceeding 80 degrees across the reservoir section and consequently resulting in doglegs. The drill-bit stood up several times in the harder shale layers, which resulted in problems of dropping of the angle (Fig.44). The slim hole equipment (e.g. mud motors and GR-MWD) proved unreliable under these drilling conditions, showing a considerable number of failures.

Furthermore, a laminar flow regime could not be maintained and turbulent flow occurred. This resulted in washouts in the more friable sand sections, coinciding with shale ledges. During pipe-conveyed logging these poor hole conditions resulted in the logging assembly parting and a density and neutron logging tool fish was left in the hole. During attempts to isolate the radioactive sources, a second fish was left in the hole, necessitating a re-drill of the sub-horizontal section (bottom hole target some 50 m away from the logging tool sources, Fig.44). Further logging with pipe-conveyed tools (e.g. CBIL) was subsequently cancelled. Similar to the first hole, poor hole conditions of this re-drill section resulted (once more) in a fish in the hole (bottom-hole assembly) and the slotted liner could eventually only be run across ca. 60% of the open hole section (Fig.44).

4.6 Results

Minor (differential) pressure depletion of only a few bars was observed within the area of the sidetrack, possibly as a result of the production from the original -102 well and the 150-200 bar pressure drop in that well, indicating that the faults had become partly transmissible as a result of the significant pressure differential. Removal of the graded rock salt filter cake and stimulation by means of a coiled-tubing wash with formic acid was successful.
Evaluation of porosity logs obtained from the first hole indicated that the well had penetrated a significant number of prolific sand streaks (Fig.45). Due to the absence of CBIL, Sonic and Production Logging Tool (PLT) data, no evidence could be obtained about the possible presence of open fractures, which had previously been observed to be occasionally present in surrounding fields.

From the GR log correlations a small fault was interpreted about halfway the well trajectory (Figs.44 and 45). Omission of strata in hole 1 (ca. 4 m) and repetition of strata in hole 2 (ca. 6 m) points to a scissor-type fault (Fig.46).

The well was brought into production and showed somewhat lower flow rates than predicted (ca. $0.5 \times 10^6$ versus $0.8 \times 10^6 \text{ m}^3/\text{day}$ at 50 bar draw down), probably due to a lower than expected permeability thickness product ($120 \text{ mD.m}$ versus $200 \text{ mD.m}$). This in turn is expected to be the result of obstruction of the open hole section due to the fish. No indications of any connectivity problems exist so far from pressure behaviour of the well.

### 4.7 Three-dimensional modelling

A three-dimensional reservoir-geological computer modelling study has been carried out covering the entire L13 East area (Fig.47) by application of the Shell proprietary computer modelling software (Geocap, Budding, Paardekam and van Rossum 1992). The results of the study were: 1) Stratigraphic compartmentalisation in the L13-FE field is expected to be equally significant as fault compartmentalisation, and 2) wells L13-FE-102 Sidetrack and L13-FE-103 are expected to connect a volumetric GIIP of $1.5 \times 10^9 \text{ m}^3$ and $1.4 \times 10^9 \text{ m}^3$ respectively. The remaining $1.7 \times 10^9 \text{ m}^3$ of gas is expected to be isolated in the southern part of the field, beyond the strike-slip faults or shear zones (Fig.39). Material balance data over the next few years may validate the predicted connectivity and may prove the necessity (if economically attractive) of an additional, future drainage point in the southern part of the field.

Such three-dimensional computer modelling studies are being applied more and more to anomalously behaving reservoirs to obtain a match with the production behaviour. The e.g. Munnekezijl Slochteren Sandstone reservoir (Chapter 5, Fig.56C, one of the recently developed, relatively small onshore gas fields to the west of the giant Groningen gas field) shows a similar behaviour as described for some of the offshore small fields. Production logs (PLTs) show that gas production is only obtained from 6-10 highly porous and permeable (1-4 Darcy) aeolian sand layers, each only ca. 1 m thick, embedded in less permeable sands (similar to the
examples given in Chapter 2; Figs. 7 and Fig. 37). However, significant and multiple shale intercalations which hamper vertical cross-flow like in the offshore K15 and L13 areas, are not present in the reservoirs of the NE Netherlands. Although the Munnekezijl production rates are high (up to $10 \times 10^6$ m$^3$/d), the wells show rapid pressure decline, strong differential depletion of the highly permeable layers and probably slow contribution to production of the less permeable sands.

The character of the thin aeolian layers in the NE Netherlands onshore region is totally different from the ones in the offshore area as described in chapters 2, 3 and 4. The highly permeable layers in the offshore K15 and L13 area most probably represent aeolian duneplace sands (remnants after erosion, e.g. Chapter 3; Fig. 26) or up to one metre high aeolian ripples / small dunes which have most likely only limited lateral extent (Fig. 48a). These have probably been deposited largely in isolation on a damp sandflat, away from the playa lake margin (Fig. 5). Core data and a high degree of correlatability of the aeolian sands of the NE Netherlands reveal that these represent laterally extensive aeolian sheet sands deposited very close to the playa lake margin itself (Fig. 48b).

For 3D modelling input, the geometries of the different facies types which dominate reservoir behaviour (e.g. aeolian dunes, sheet sands and shales from playa lake/mudflats and ponds) are of paramount importance. Statistical data sets for a range of facies types have been obtained from outcrops of the upper part of the Permian Cutler Group, Utah (Fig. 49, NAM sponsored TU Delft extramural research project; Visser 1998), which represents an excellent analogue for the Slochteren Sandstone reservoirs. The data sets are currently being applied successfully in modelling exercises for a number of small Rotliegend reservoirs in the NE Netherlands.

Similar to the small Rotliegend reservoirs in the offshore K15 and L13 area, compartmentalisation by (sub)seismic faulting is also suspected for the onshore reservoirs in the NE Netherlands. However, seismic attribute maps that may indicate the presence of such faults (e.g. Figs. 11, 34 and 39) are frequently non-conclusive in this area. In the NE Netherlands the overlying Zechstein salt package exhibits an often more domal to saltwall character (Chapter 5) and the salt package contains numerous, isolated floating blocks of Zechstein 3 anhydrite, which generate artefacts on the seismic attribute images.

Over the last years geochemical techniques are being applied more and more to detect differences in rock, fluid and gas composition. For example, geochemical fingerprinting of the Munnekezijl reservoir has indicated that the apparently
discontinuous fault between the blocks that contain wells MKZ-1 and MKZ-2 (Fig.56C) has a sealing character, probably as a result of cataclasis due to strike-slip movements:

1) Differences in gas composition (Nitrogen and Methane isotopes) between the two blocks.

2) Differences in Strontium isotope ratios (87Sr/86Sr). These isotope ratios have been analysed from residual salt (contained in residual formation water in the gas zone) and the differences indicate different timing of gas charge between both blocks.

3) K/Ar isotope measurements on illite clay minerals have revealed that the illites of the MKZ-1 block are ca. 100 mln years younger than those of the MKZ-2 block.

These measurements indicate that the MKZ-1 block underwent gas charge some 100 mln years later (Tertiary charge) than the MKZ-2 block (Jurassic-Cretaceous charge). This is also reflected by lower porosity and permeability of the MKZ-1 well, related to ongoing diagenetic processes in the MKZ-1 block in the water leg, whilst diagenesis in the already gasfilled MKZ-2 block had already come to a halt. Such sub-seismic sealing faults are being applied in the 3D Geocap models to obtain a match with the actual, measured gas connectivity of the different reservoir blocks, to locate undrained areas and for planning of possible infill wells.
CHAPTER 5

Wrench tectonic signatures: Prediction of open fracture systems and prospectivity in Zechstein gas reservoirs, NE Netherlands

Abstract

Economic gas productivity from overall tight Zechstein 2 carbonate reservoirs in the NE Netherlands is dependent on the presence of major open fracture zones. Some 5400 fractures have been studied from cores and borehole imaging logs with the aim to predict their orientation and spacing. This was done to capture the optimum benefits from horizontal drilling techniques, to maximise the overall recovery efficiency and to extend the life cycle of the sour gas system.

Analysis by the author of the regional structural deformation history, in which the Lauwerszee Trough plays a dominant role, has resulted in a revision of the concepts regarding the origin of fractures. In addition to dip-slip, strikeslip signatures are ubiquitous in the whole of the NE Netherlands. A complex interplay of dominantly NW-SE oriented wrench tectonics has been active from Carboniferous times to the present. The orientation of fracture patterns, measured from cores and supported by signatures from borehole image logs, is in line with the synthetic and antithetic Riedel shear faults and extensional trends related to wrenching. Approximately 1050 open fractures represent largely N-S striking extensional and/or dilational antithetic Riedel shear systems, which display a fractal relationship with the major faults. The fracture systems intersect at acute angles, forming an interconnected network and provide the dominant control on permeability in overall tight carbonate reservoirs.

Analysis of the spatial relationship between large-scale wrench faults and associated smaller faults in the NE Netherlands, complemented by small-scale fault and fracture signatures from a number of outcrop analogues, has resulted in a novel, empirical model for predicting the spacing of major open fracture systems. Subtle lineaments on 3D seismic attribute maps are in line with the measured orientations and contribute to locating open fracture zones. The model is supported by the results of eight recently drilled, approximately E-W oriented (sub)horizontal wells and sidetracks, showing up to 300-fold...
productivity improvements, when compared to non-fractured vertical wells. Consequently, a significant number of poorly producing wells have become candidates for sidetracking. A number of blocks previously discarded as non-reservoirs have now been identified as potential producible reservoirs, resulting in scope for recovery of several billion m$^3$ of gas.

Wrench tectonic deformation features like reverse faults and folds explain the development of palaeo-highs which in turn triggered the generation of carbonate platforms along the edge of the Zechstein basin. Additional build-ups are expected along wrench faults in more basinal parts, northward of the main platform areas. Such so-called off-platform highs are known from several locations in Germany. A number of possible carbonate build-ups have already been recognised from 3D seismic and this may lead to additional appraisal of potential gas reserves.


5.1 Introduction

The Late Permian Zechstein deposits in W Europe consist of a cyclic sequence of carbonate and evaporitic rocks. Up to 5 cycles have been identified, locally initiated by thin clastic deposits, passing upward in turn through carbonate, anhydrite to halite deposits.

Gas production from Zechstein Carbonates started in the 1950's from Zechstein-2 Carbonates (ZEZ2C) for local household supply (Coevorden area, Fig.50). During the 1960's to 1970's most of the ZEZ2C reservoirs in SE Drenthe and Twente, including Zechstein-3 Carbonate (ZEZ3C) reservoirs, were brought into commercial production. The sour gas was initially transported to treatment facilities in Germany until the start-up in 1988 of the sour gas desulphurisation plant in Emmen. H$_2$S concentrations in the ZEZ2C reservoirs vary considerably in the area, ranging from almost zero to ca. 50%.

In order to extend the economic life of the desulphurisation plant a significant addition to the remaining sour gas reserves is required. Recent evaluation of the area has indicated the presence of a number of potential ZEZ2C
appraisal/exploration prospects. In addition, in order to improve productivity and connectivity of known reservoirs, horizontal drilling techniques, short radius sidetracks, multi-lateral holes, underbalanced coil-tubing drilling and hydraulic fracturing techniques are being planned for and applied.

The ZEZ2C consists of an E-W trending carbonate platform (Clark 1980a,b, Van der Baan 1990). The platform carbonates are bounded by lagoonal facies to the south, slope facies to the north and west and basinal facies further north (Fig.51). The platform deposits exhibit the overall better reservoir quality (Van de Sande et al. 1996), whereas lagoonal, distal slope and basinal deposits are tight. Proximal slope deposits may have good reservoir quality as a result of the presence of platform-derived material deposited as slumps and breccias.

In addition, good quality ZEZ3C gas reservoirs exist in the Twente area, where a ZEZ3C platform developed more to the south of the main ZEZ2C platform. No reservoirs in the ZEZ3C in the SE Drenthe area have been encountered yet since it consists only of basinal deposits in the form of tight floating blocks in Zechstein salt. The ZEZ1C consists of overall thin and tight basinal deposits and no producible reservoirs have been discovered so far.

A large number of ZEZ2C reservoirs consist of poor quality basinal distal slope deposits (Fig.51, porosities of 1-2%) with overall very poor well productivities (Fig.52, as little as some 20,000 m³/d). Better productivities are obtained from the more porous and permeable proximal slope to platform deposits (pack- to grainstones, with varying degrees of leaching). However, wells that have encountered major open fractures (indicated by significant mud-losses during drilling) show the best productivities, i.e. rates in excess of 0.5 x 10⁶ m³/d and up to 6.5 x 10⁶ m³/d (Fig.52, well OSH-3).

Since 1990 some ten different fracture studies have been carried out, mainly by student trainees, for single wells and reservoirs. Fracture orientations have been measured either relative to palaeo-magnetically oriented cores or relative to unambiguous bedding-dip orientations. Three types of fractures were recognised: extensional, shear and dilational shear / hybrid fractures.

5.2 New interpretation of the origin of fractures

The origin of fractures in Zechstein carbonates of the NE Netherlands has previously been interpreted to be the result of the following factors: 1) proximity of faults, 2) proximity of the platform edge and 3) the effects of overburden loading and folding. In such an extensional setting the maximum principal stress is vertical and hence vertically oriented extensional fractures would be expected to be
common. Instead the most common fractures are crossing shear fractures with an apparent 'horst and graben' configuration. This is inconsistent with an assumed extensional stress regime. The observed accommodation space problem between the horst and graben features is best explained by wrench tectonics (Fig.53, Frikken 1996c). The interpretation of horizontal stress anisotropy is furthermore supported by the occurrence of reverse fractures and by the frequent occurrence of vertical stylolites in cores.

Wrench tectonic signatures in the subsurface of the Netherlands and the North Sea Basin have been reported previously (e.g.Ziegler, 1975, 1978, Speksnijder 1987, Oudmayer and de Jager 1993, Van Wees and Cloetingh, 1995, Ziegler 1975, 1990, Ziegler, Cloetingh and van Wees 1995, Chapters 2, 3 and 4 of this thesis and Frikken 1996c). For proper analysis of fractures in the ZEZ2C reservoirs, wrench tectonic signatures have been analysed by the author on a regional scale across the NE Netherlands.

5.3 Overall structural deformation history of the NE Netherlands

Besides recognition of dip-slip patterns of faults, which is best done in cross-sections, an important criterion for recognising strike-slip deformation features is the character of fault patterns in plan view, especially from 3D seismic dip-maps. The Lauwerszee Trough, in-between the Groningen Block and the Friesland Plateau (dip-map Fig.54, approximately the same area as Fig.50), is bounded to the west and east by major NW-SE trending fault zones, respectively the Hantum fault zone and the W Groningen fault zone. These fault zones show the signatures of dextral (right-lateral) wrenching along deep-seated basement faults with related overall NNW-SSE oriented compression, originating from the Carboniferous Variscan orogeny (Ziegler 1990). The largely NNW-SSE oriented en echelon fault pattern along the Lauwerszee Trough represents left-stepping synthetic Riedels, characteristic for dextral wrenching.

Such features are known from the central North Sea area (Chapters 2, 3 and 4 of this thesis), as well as from outcrops (e.g. Holocene surface expressions of this type of faults in the Tadzhikistan-Kyrgyzstan area, Streeker et al. 1995). Furthermore, laboratory sandbox experiments have confirmed the development of this type of deformation features as a result of wrenching along basement faults (Biddle and Christie-Blick 1985, Richard et al. 1991, 1995). The features develop together with a range of additional deformation features like antithetic Riedel faults, reverse faults, folds and extensional faults (insert Fig.54).
The Lauwerszee Trough developed (at least) during the Late Carboniferous in response to E-W transtension caused by NW-SE dextral wrench movements ("during the Westphalian, terminal phase of the Variscan orogeny, compressional stresses exerted again over the European foreland at distances up to 550 km north of the Variscan thrust front", Ziegler 1990). The early development of the Lauwerszee Trough is evident from Permian subcrop maps and Rotliegend isopach maps, showing significant thickening as well as thinning of sediments across faults. The mostly ENE-WSW trending faults within the Lauwerszee Trough (Fig.54) are interpreted to represent antithetic Riedels (at an obtuse angle to the basement wrench faults). These antithetic Riedels, as well as the synthetic Riedels, exhibit significant strike-slip components (up to 750 m) besides significant dip-slip components (up to 400 m).

Continued wrenching along the major NW-SE faults resulted in rotation of the fault blocks within the Lauwerszee Trough together with strike-slip movements on the antithetic Riedel faults. Similar configurations of rotating fault blocks in-between two major wrench fault systems are known from the Las Vegas Valley Shear Zone in S Nevada (Sonder et al. 1994), the North Pyrenean Aquitaine Basin (Bourrouilh et al. 1995) and the Karakoram area (Searle 1996).

Moreover, the major wrench faults have also been subject to sinistral wrench movement, probably during Early Kimmerian deformation phases. A dip-map of the Jurassic Base Altena Group (only present in the SE Drenthe area due to a Lower Cretaceous erosional unconformity to the north) reveals N-S oriented right-stepping Riedels along the Holsloot fault zone (Fig.55), characteristic for sinistral wrench movements. Associated with this type of deformation, the e.g. neighbouring Emmen and Schoonebeek areas have undergone dextral strike slip, near-perpendicular to the major Holsloot wrench fault, characterised by the presence left-stepping Riedels (Figs.55 and 56A; ‘Since the Carboniferous, no orogenic movements are recognised in the Netherlands,...only vertical fault movements are assumed’, Heybroek 1974).

Associated NW-SE oriented horizontal compression resulted in additional, significant folding in this area (Fig.56B). Similarly, sinistral reactivation of the Lauwerszee boundary faults resulted in dextral reactivation and significant lateral offset along the antithetic Riedels (Fig.56C) and the generation of a number of 'pull-apart basins' (e.g. Fig.56D).

The wrench fault systems of the Lauwerszee Trough branch to the northwest and are probably linked to the younger fault systems bounding the Central Graben.
Branching configurations are characteristic for the subsurface of the Netherlands (Oudmayer and de Jager 1993, Remmelts 1996), e.g. the NW-SE trending Roer Valley Graben, being a northwestern branch of the N-S trending Rhine Graben system (Geluk et al. 1994). These branching configurations of major faults are characterised by rhomboidal fault patterns (Fig.54), e.g. the Anjum area and the Coevorden-Dalen-Oosterhesselen area in between the Holsloot and Coevorden wrench fault zones.

It is evident that wrenching continued through time in the NE Netherlands as is illustrated by the presence of flower structures at various stratigraphic levels (Fig.56E) and at various scales (Fig.56F). The Late Kimerian, Laramide and the Late Alpine orogenic phases resulted in N-S to NNW-SSE compression and reactivation of the dextral wrench movements in the NE Netherlands ("intra-plate deformations related to plate collision .... can occur at distances of up to 1600 km from a collision front", Ziegler, Cloetingh and van Wees 1995).

A Base Tertiary dip-map (Fig.57) shows en echelon left-stepping Riedels along the wrench fault zones of the Lauwerszee Trough. The W Groningen fault appears to connect to the Holsloot fault zone between the Emmen and Dalen/Oosterhesselen areas, whereas the Hantum fault appears to connect to a wrench fault zone north of Coevorden. These major wrench fault systems actually show a 'meandering', offset pattern with an E-W dextral offset south of the Eleveld area (Fig.57).

On the dip-map of Figure 57, the presence of the Riedel zones is accentuated by piercement of Zechstein salt, which has moved upwards along the fault planes, probably as a result of wrenching related transtensional forces ("buoyancy alone cannot drive salt diapirism through a brittle overburden....regional extension or compression could be a necessary mechanism likely to promote salt diapirism", Daudre and Cloetingh 1994).

The wrench tectonic signatures as described here and those described in the following paragraph are considered to be in full reconciliation with the criteria as proposed by Harding 1990.

5.4 ZEZ2C fracture patterns in SE Drenthe

The orientation of the major wrench tectonic compressive stresses can, in addition to expressions on dip-maps, best be deduced from the orientation of pop-up blocks, bounded by reverse faults. Such features develop perpendicular to the horizontal maximum principal stress (insert Fig.54 and 58). Several significant reverse faults
are present in the SE Drenthe area and their orientation is largely E-W (Fig.59), indicating an overall N-S oriented maximum principal stress. At the end of the Carboniferous such (syn-sedimentary) reverse faults probably generated palaeo-highs on which the ZEZZC platform has developed.

Fracture data have been compiled from previous studies and the rose-diagram of all 5402 predominantly subvertical fractures measured from 12 cored wells of the SE Drenthe area (average well spacing ca. 5 km) clearly shows 3 populations in orientation (Fig.60A, some 4346 fractures filled by dolomite, halite or anhydrite and 1056 open fractures). The orientations of these fractures are fully reconcilable with the orientations of synthetic Riedels, antithetic Riedels and extensional fractures. Similar trends are observed for all individual wells and reservoirs.

A rose-diagram of fracture data from three wells where borehole imaging logs have been taken, shows a similar orientation of fracture populations (Fig.60B). The rose-diagram of the 1056 open fractures reveals 2 populations of dominant orientations striking 175°N and 35°N (Fig.60C). These orientations are in line with the extensional and antithetic Riedel (dilational shear) fracture trends.

The presence of open fractures may indicate that these have been generated as a result of the younger orogenic phases, largely during and after the main gas charge events (Jurassic-Cretaceous and Tertiary), the hydrocarbons preventing cementation by dolomite, halite and anhydrite ("compressive stress will generate appreciable fluid flow as pore pressure increases, resulting in natural hydraulic fracturing and fluid escape", Zoback et al. 1993; however, these conditions without gas-fill still allow precipitation of cementing minerals).

The wrench-related origin of fractures as presented here is complementary to the fold-related origin of fractures (Stearns and Friedman 1972). A fold-related origin has been proposed for the Zechstein carbonate reservoir of the Hewett Field in the UK Southern North Sea Basin (Cooke-Yarborough 1994), although the author does not rule out that: "Alternating left-lateral and right-lateral strike-slip movement over geological time on the high-angle NW-SE trending Dowsing Fault system could have generated high-angle, essentially N-S fractures during transpressive movements".

The present-day horizontal maximum principal stress in the NE Netherlands, as indicated by borehole breakouts from several Borehole Imaging logs, ranges between NW-SE and N-S, dependent on the local stress regime of individual blocks. This orientation is also evident from hydraulic fracture stimulation of Rotliegend reservoirs (Fig.61). Their orientation is largely in line with the overall stress-fields across W Europe (Klein and Barr 1986, Gruenthal and Stromeyer
1994). This present-day maximum principal stress is largely parallel to the extensional open fracture trend and has probably contributed to their preservation. These open fractures are extremely important for reservoir quality as "fractures that are parallel to the in-situ maximum horizontal stress may provide the dominant control on reservoir permeability" (Teufel 1994).

A total of eight recently drilled, largely E-W oriented horizontal to sub-horizontal wells and sidetracks support the evidence for the predominant N-S orientation of open fracture systems. These wells encountered significant mud-losses during drilling and show up to 300-fold productivity improvements when compared to non-fractured wells in similar tight carbonates (Fig.52, 0.02 x 10^6 m^3/d from well OSH-1 versus 6.5 x 10^6 m^3/d from horizontal well OSH-3).

The prevalence of extensional and antithetic Riedel fractures, which intersect at acute angles, is likely to provide an interconnected network throughout the reservoirs (insert Fig.52), enlarging the inflow area from the overall tight carbonate matrix. This is supported by the significant fact that wells that are producing from open fracture systems show relatively slow depletion rates.

5.5 **Predictive model for fracture density / spacing**

The Lauwerszee Trough represents a large-scale tectonic configuration of two parallel wrench faults, with near-perpendicular faults in between, interpreted as antithetic Riedels (Fig.54). The ratio between the spacing of the boundary faults of the Lauwerszee Trough and the spacing of associated antithetic Riedels ranges from ca. 10:1 to ca. 20:1.

A medium-scale analogue of parallel wrench faults with associated near-perpendicular antithetic Riedels and/or rotated extensional fractures has been found by the author in outcrops of the Carboniferous Ross Sandstone, County Clare, SW Ireland (Fig.62A/B). In that case the spacing ratio between the main wrench faults and the associated fracture systems also ranges from ca. 10:1 to ca. 20:1. Additionally, a very small-scale analogue of wrench faults and associated fractures was found by the author in outcrops of Upper Carboniferous shallow-water carbonates of the Pennsylvanian Paradox Formation in SE Utah (Fig.62C), showing similar ratios of ca. 10:1 to 18:1. Furthermore, a possibly comparable system of parallel faults perpendicular to a major fault system is seen from an aerial photograph of the southeastern part of the Tibesti Mountains, Chad, Africa. Although the existence of parallel wrench faults in this system is not clear, the spacing between the smaller faults is consistently ca. 250 metres (Fig.62D), which
is in line with the spacing of open fractures as calculated for the Emmen reservoir in SE Drenthe (see text below).

Assuming an empirical relationship between the large-scale Lauwerszee Trough example and the smaller-scale outcrop analogues of Ireland and Utah, these spacing ratios have been applied to the ZEZ2C reservoir blocks in SE Drenthe.

The relationships were applied to the Emmen field which, compared to the Lauwerszee Trough and the outcrop analogues, shows a similar configuration but of intermediate dimensions (Fig.63). The distance between the E-W trending boundary faults is on average ca. 5 km. From the above ratios of 10:1 to 20:1, a range of 250-500 m spacing is calculated for the approximately NNW-SSE striking, major open fracture systems of the Emmen field. A recently drilled E-W horizontal sidetrack of well EMM-8 (Fig.63B) encountered total losses of drilling fluid (and hence a major open fracture system) after about 250 m of trajectory.

The spacing ratios presented here are not very accurate and data quality would benefit from a larger database. However, it is of interest to note that a relationship between wrench faults and related faults/fractures is not known to date from literature. Detailed analysis of fault spacing has been reported from the e.g. northern North Sea area (Watterson and van Veen 1994), however, the dataset primarily refers to normal faulting.

The rather large spacing of open 'mega' fractures/small faults as presented here exceeds the maximum values of the Probability Density Functions of fracture spacing as presented by Priest and Hudson (1976) and by far exceeds the average fracture spacing as presented by Narr (1996). However, this is probably due to the fact that in this case only the major open fracture systems are being considered: fracture apertures as wide as 25 - 35 cm have been identified from CBIL log analysis (Circumferential Borehole Imaging Log, Western Atlas, Fig.64), reflecting the presence of open fault systems rather than fractures ("microfracture strike is a good guide to the strike of macrofractures that formed concurrently ..... macrofractures are generally more widely spaced and easily missed, whereas microfractures are more common", Laubach 1996). It is of interest to note that the spacing of individual hairline fractures in the Zechstein reservoirs is in the order of decimetres to metres.

It is of interest that in the analogues of Ireland and Utah, en echelon, synthetic Riedel shear fractures also occur at acute angles to the main wrench faults (Fig.65). This configuration of synthetic Riedels is in line with those observed in the NE Netherlands and SE Drenthe areas (e.g. Figs.54 and 57: W Groningen fault zone and Figs.55 and 56A: Emmen area).
Attempts are made to detect the orientation and location of the major open fracture systems and/or small open faults from 3D seismic attribute maps. However, the results are largely depending on seismic quality, which is frequently poor due to the presence of thick Zechstein salt and scattered Zechstein 3 floating blocks above the reservoirs. An illumination dip-map of top ZEZ2C of the central Emmen area (the EMM-8 horizontal sidetrack area) reveals largely NNW-SSE striking lineations (Fig.66), which may well represent large-scale open fracture systems and/or small open faults.

The lineations on the central Emmen dip-map have a spacing in the range of 250 - 500 m, which is consistent with the spacing inferred from the large- and small-scale analogues of the Lauwerszee Trough, the outcrop analogues and the drilling results of well EMM-8 sidetrack. This inferred spacing is furthermore consistent with the 'rule of thumb stating that fracture spacing is commonly closely related to bed thickness' (Lorenz et al. 1996; the average thickness of total Basal Zechstein is ca. 220 m in the Emmen area).

5.6 Possible additional ZEZ1C and ZEZ2C off-platform build-ups

To the north of the main ZEZ2C platform, a number of ZEZ2C reservoirs have been discovered, representing isolated carbonate build-ups, e.g. Exloo, Gasselternijveen and Vlagtwedde (Fig.50). Differential fault throws at top Basal Zechstein, top Carboniferous and intra-Carboniferous levels imply local syn-sedimentary faulting. Furthermore, thin, isolated deposits of the Rotliegend Slochteren Sandstone (which was overall not deposited in SE Drenthe) have been encountered locally in the area indicating the presence of local graben's resulting from syn-sedimentary faulting. Such syn-sedimentary faults may have created local palaeo-highs triggering the development of isolated carbonate build-ups.

These carbonate build-ups are located close to the major wrench fault zone connecting the W Groningen wrench fault and the Holtsloot wrench fault (Figs.54 and 57). The carbonate platform of Vlagtwedde is located above the 'Vlagtwedde' fault, which probably represents a southern extension of the major Ems fault zone, which occurs east of the major Groningen High, being parallel to the wrench faults bounding the Lauwerszee Trough. These major wrench fault zones have probably triggered the development of local palaeo-highs (pop-ups/restraining bends/shearing zones).

The ZEZ1C and ZEZ2C deposits in the Groningen area mainly consist of deeper water / basinal, tight carbonate mud deposits. However, drill-cuttings from a
number of wells close to the wrench fault systems have been investigated and these clearly show the presence of carbonate platform debris, columnar stromatolites and well rounded oncoids at ZEZ1C level, indicating the presence of shallow water deposits. Also from the ZEZ2C level indications of shallow water carbonate deposits are evident from a number of locations. These observations indicate the possible existence of additional carbonate build-ups and reservoir development north of the main platform areas.

Off-platform highs of the ZEZ2C are known from the subsurface of NE Germany (Strohmenger et al. 1993). Similarly, off-platform highs of the ZEZ1C are known from outcrops in the Harz Mountains area (Paul 1980, 1986, 1992). The ZEZ1C off-platform build-ups in the Harz area occur some 100-150 km north of the palaeo-coastline, i.e. the Thueringia area in Germany, where the major ZEZ1C build-ups are present (Paul 1995).

The Harz build-ups have developed on a largely N-S trending regional palaeo-high (the Eichsfeld Schwelle), which may represent an active basement fault lineament, similar to the Hantum, W Groningen, Coevorden and Holsloot fault zones. Furthermore, off-platform build-ups are known from outcrops in the Osnabrueck area (Paul 1986), the development of which has probably been triggered by palaeo-highs along the eastern continuation of the Gronau and Oesning reverse fault trend.

As mentioned previously, rhomboidal fault patterns are well known from the Netherlands and the North Sea basin (Wride 1994) in areas where major wrench fault systems branch. Such NNW-SSE and WNW-ESE patterns are interpreted as conjugate sets of Riedel faults resulting from E-W oriented dextral wrenching (Fig.67). Small-scale analogues for such configurations have been found in outcrops of Precambrian (Upper Brioverian) sandstones in Brittany, France (Fig.68A), the Carboniferous Ross Sandstone of County Clare, Ireland (Fig.68B), as well as the Upper Rotliegend Cornberg Sandstone in Hessen, Germany and shallow-water carbonates of the Pennsylvanian Paradox Formation in SE Utah. The associated reverse fault and folding trends (Fig.67) have been observed in Brittany, France (Fig.69A) and in SE Utah (Figs.69B).

Such type of larger-scale reverse fault and fold configurations have probably also existed in the NE Netherlands during Permian times, controlling the generation of off-platform build-ups. Indications for a number of possible build-ups have already been identified. From core material of a number of wells in the SE Drenthe area the presence of volcanic material at the base Zechstein is evident and chlorite minerals have been observed from ZEZ1C cores. This supports the concept of
tectonic activity during Permian times (compression, reverse faulting, associated volcanic expulsion and generation of palaeo-highs). As an example, the ZEZ1C Roemerstein reef complex of the Harz Mountains, Germany (Paul 1980) has developed on top of volcanic deposits.

A number of largely NE-SW striking seismic anomalies (thickening events in time) have been identified in the NE Netherlands (e.g. Fig.70). This trend coincides with the underlying reverse fault/fold trend (cf. the NE-SW trending Aachen Thrust on the German-Dutch border near Limburg, Geluk et al. 1994). Additional red loops on seismic sections at ZEZ1C level are interpreted to be indicative of possible porous ZEZ1C build-ups (Fig.71) and these warrant appraisal drilling.
CHAPTER 6

New concepts regarding Carboniferous reservoirs in the NE Netherlands *

Abstract

Upper Carboniferous gas reservoirs have been developed from the early 1970's onwards. The reservoirs consist of fluvial channel sandstones alternating with floodplain shales. Well productivities vary from 0.03 - 1 x 10⁶ m³/d. The poor productivities are mainly obtained from reservoirs with 2-8 m thin meandering channel deposits which have overall low permeabilities. The better productivities are obtained from 20-25 m thick braided channel deposits. The reservoirs show a wide range of recovery factors varying from 90% down to ca. 10%. Field reviews and studies have been delayed so far due to the rather complex architecture. However, economical considerations and recent development of novel geophysical and computer modelling techniques warranted the initiation of multi-disciplinary studies to address the connectivity problems and to possibly produce the remaining several billion m³ of gas reserves before the shut-down of the ageing production and evacuation systems.

Correlations of channel sands from some 70 wells in the area have been revised based on continuous coals and chemostratigraphic analyses. Syn-sedimentary activity of major wrench fault systems in the NE Netherlands appears to have had a strong control on the fluvial depositional patterns, a feature well-known from a number of reservoirs in other parts of the world. Besides lateral variation in the type of channel deposits, also well-defined vertical sequences have been identified. Each cycle starts with laterally extensive, 20-25 m thick multi-storey braided channel deposits overlain by laterally discontinuous, 2-8 m thick meandering channel and crevasse splay deposits, representing a labyrinth-type reservoir character. A comparable architecture is known from nearby outcrops of U Carboniferous deposits in W Germany as well as Kentucky.

An extensive dataset on sandbody geometries was obtained from literature and palaeocurrent data were obtained from borehole image logs for input into 3D modelling. A 3D GeocaP model was generated as a pilot for the
underperforming Den Velde field. The model indicated a reduction in GIIP. This is mainly due to the fact that the meandering channel deposits in the upper part of the reservoir have been modelled as discontinuous bodies, in contrast to the conventional GIIP calculation envisaging corellatable bodies. The model was calibrated and validated by a novel technique, i.e. constraining the model by importing porosity and net sand volumes obtained from seismic inversion. This model also showed a reduced GIIP which is in line with the GIIP as obtained from the prior model. The seismically constrained model revealed the presence and distribution of scattered meandering channel sands in the labyrinth-type upper part of the reservoir and also indicated the presence of sub-seismic faulting in the thicker braided channel complexes. A study is ongoing to economically and technically access the remaining GIIP, isolated in compartments, by horizontal drilling and hydraulic fracturing.

This study, involving state of the art technology, will act as a template in further studies for possibly accessing remaining reserves within a number of anomalously producing Carboniferous reservoirs in the NE Netherlands. The good match in GIIP between the prior deterministic and the seismically constrained model is expected to provide a unique opportunity for appraisal of so far un-drilled blocks of the SE Drenthe area in which well planning may be based on the signature of seismic inversion data.

* Author: Frikken, H.W. Presented at the Carboniferous workshop: Facies architecture, cyclicity and sequence stratigraphy of Upper Carboniferous reservoirs, 7 - 9 November 1997, Osnabrueck, Germany.

6.1 Introduction

Carboniferous gas reservoirs in the NE Netherlands have been in production since the early 1970's (Tubbergen) and early 1980's onwards (Coevorden, Fig.72). The reservoirs consist of fluvial channel sandstones alternating with floodplain shales of Upper Westphalian C to Lower Westphalian D age (i.e. mainly the Tubbergen Sandstone Formation, overlying the coalbearing Maurits Productive Measures). No indications exist of the presence of coastal deposits and/or marine shales within the Westphalian sequence.

The strata are generally dipping at angles of around 3 degrees to the east below the Saalian unconformity. Some of the reservoirs are strongly faulted like e.g. the Coevorden field that consists of ca. 50 separate blocks varying in size between 0.2 and 5 km².
Well productivities show a wide range varying from ca. $0.03 \times 10^6 \text{ m}^3/\text{d}$ (e.g. Emmen, Dalen, Oosterhesselen) to ca. $1 \times 10^6 \text{ m}^3/\text{d}$ (e.g. Tubbergen and Hardenberg). The poorer productivities are mainly the result of poor quality fluvial sandstones at some of the stratigraphic levels together with a varying degree of diagenesis. The reservoirs also show a wide range of recovery factors, varying from 90% down to around 10% (Fig.72). Although the Coevorden reservoir shows an average recovery of 60%, significant connectivity differences are noted between the separate fault blocks.

Recent reviews indicated considerable scope for recovery of several billion m$^3$ of gas. Because of an expected end of the Carboniferous production and gas evacuation systems by 2015, all remaining reserves should be developed and produced by then. A multi-disciplinary study has been initiated in 1997 to investigate the complex reservoir architecture and production performance with initial focus on the reservoirs of SE Drenthe. 3D reservoir-geological modelling studies are ongoing and aimed at optimisation of production performance, recovery efficiency and development strategy (number, location, type and orientation of wells, including possible hydraulic fracturing). A number of infill/re-development are already planned from 1999-2000 onwards.

### 6.2 Reservoir architecture

Log correlations of the Upper Carboniferous sandstones of some 70 wells have been re-evaluated and revised, based on: 1) the character of fluvial deposits from core data, 2) coals, which are in general laterally very correlatable and not often affected by erosion, because after deposition peats are very cohesive resulting in channel avulsion and laterally extensive sandstone belts, and 3) chemostratigraphy: analysis of heavy mineral associations which are not affected by diagenetic processes.

Overall, the thicker multi-storey sandstone sequences (mainly braided channel deposits) can be correlated across kilometres to even tens of kilometres. However, in a number of locations these sandstone bodies 'disappear'/shale-out across a few hundreds of metres. Such features are interpreted to be the result of syn-depositional fault activity (Fig.73).

Figure 72 shows conceptual contours of better sand development and probably related higher recovery factors across the NE Netherlands. The mapped trend coincides with the trend of the Coevorden-Holsloot wrench faults, which were most likely active during U Carboniferous deposition (the fault trend is best expressed by
the base Tertiary dip map of figure 57). The subcrop of the Tubbergen Sandstone shows a similar largely NW-SE to N-S trend, indicating reactivation of these faults at the end Carboniferous (Saalian unconformity). Syn-sedimentary fault control on fluvial systems is a well-known feature, e.g. in the Upper Oligocene to Lower Miocene of the Lorance Basin, Spain (Van Veen 1994), the Westphalian C, Belgium (Dreesen et al 1995), the Pennsylvanian Minturn Fm., Colorado (Houck 1997), the U Cretaceous Almond Formation (Mesa Verde Group), Wyoming (Clawson and Favret 1997) and the Eocene Prodtuttivo Fm., Italy (Thorez, Bottiro and Dreesen 1997). Hampson, Stollhofen and Flint (1997) recognised steep-sided flanks of Upper Carboniferous multi-storey braided channel deposits of the Ruhr area, Germany, possibly indicative of syn-sedimentary faulting. Even the orientation of present-day major river systems such as the Ems (Ems Graben), Rhine (Rhine Graben), Ruhr (Ruhr Graben), as well as the Mississippi, Missouri, Amazon, Brahmaputra and Nile rivers are most likely controlled by subtle surface expressions of major basement faults.

Besides lateral variation in fluvial depositional patterns, also vertical sequences have been recognised in the SE Drenthe area (based on core data and log correlations). The Upper Carboniferous deposits consist of a number of repeated sequences, starting at the base with thick multi-storey braided channel deposits, grading upwards into thinner meandering channel pointbar and crevasse splay deposits, separated by floodplain shales (Fig.74). Similar sequences, however, with overall thinner floodplain shale intercalations, are present in outcrops of Westphalian C/D of the Osnabrueck area in NW Germany (Fig.75a/b). The Tubbergen Sandstone sequences in SE Drenthe probably represent a westward, more distal equivalent of these deposits.

A combined lateral and vertical association of (laterally extensive) multi-storey, braided channel deposits and (laterally less extensive) meandering channel deposits, comparable to those encountered in SE Drenthe, has been reported from Carboniferous outcrops in E Kentucky (Ferm and Weisfluh 1989, Ferm 1990).

6.2.1 Braided channel deposits

The thick multi-storey braided channel deposits generally provide good quality reservoirs with overall better permeability (up to tens of milliDarcies) compared to meandering channel deposits (up to only 10 mD), mainly as a result of overall coarser grain size. Intercalated shale layers are frequently not laterally extensive, being eroded by overlying channels and resulting in overall good connectivity
Carboniferous reservoirs

(layercake-type reservoirs, e.g. Figs.75a and 76). This type of deposits is characterised by dominant downstream accretion bar forms and less common lateral accretion pointbar deposits. Core data show that the associated floodplain shales represent poorly-drained palaeosols (grey to dark grey, reducing conditions, Besly and Fielding 1989). This type of perennial channel sand deposits may be laterally very extensive as indicated by log correlations and by production behaviour in the NE Netherlands, as well as from published outcrop data:

<table>
<thead>
<tr>
<th>Study</th>
<th>Thickness</th>
<th>Width</th>
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<tr>
<td>Hampson et al. 1997a</td>
<td>20 - 40 m</td>
<td>10’s of kms</td>
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<td>U. Carbonif., UK and Ireland</td>
<td></td>
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<tr>
<td>Hampson et al. 1997b</td>
<td>20 - 50 m</td>
<td>2 - &gt;5 km</td>
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<tr>
<td>U. Carbonif., Ruhr area, Germany</td>
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<tr>
<td>Glover and Jones 1997</td>
<td>10 – 20 m</td>
<td>10’s of kms</td>
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<td>U. Carbonif., NW Germany</td>
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<tr>
<td>Houck 1997</td>
<td>average 20 m</td>
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<td>U. Carbonif., Colorado</td>
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<tr>
<td>Robinson and McCabe 1997</td>
<td>20 – 33 m</td>
<td>1 – ca. 10 km</td>
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<tr>
<td>U. Jurassic, S Utah</td>
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6.2.2 Meandering channel deposits

Meandering channel deposits in the NE Netherlands consist of thinner, dominantly single-storey sands, mainly lateral accretion pointbar deposits and crevasse splay sands embedded in floodplain shales. These deposits have overall less good reservoir quality compared to braided channel deposits. Core data show that the associated floodplain shales represent well-drained palaeosols with a characteristic red-brown colour (e.g. Fig.75b: oxidising conditions, ferruginous, calcareous, mottled, frequent presence of rootlet traces, Besly and Fielding 1989).

The lateral extent of these deposits is typically far less than the braided channel sands and these pointbar deposits frequently form labyrinth-type reservoirs. A significant number of outcrop analogues illustrate that such type of isolated, ephemeral channel meander belt deposits are common features (Figs.77 and 78). Even the individual meander belt sand bodies may suffer from severe internal compartmentalisation, i.e. shale and cemented intercalations between individual lateral accretion sand packages (Fig.79).
For stochastic 3D modelling purposes of this type of deposits for the Carboniferous reservoirs of SE Drenthe an extensive numerical data base has been obtained from published outcrop data, e.g.:

<table>
<thead>
<tr>
<th>Source</th>
<th>Thickness</th>
<th>Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atkinson 1988</td>
<td>2.3 - 8 m</td>
<td>18 - 226 m</td>
</tr>
<tr>
<td>Tertiary, N Spain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collinson 1978</td>
<td>1 - 18 m</td>
<td>20 - 2000 m</td>
</tr>
<tr>
<td>Compilation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cueva Gozalo and Martinius 1993</td>
<td>0.7 - 8.5 m</td>
<td>7 - 90 m</td>
</tr>
<tr>
<td>Tertiary, Central Spain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glover and Jones 1997</td>
<td>8 - 15 m</td>
<td>100 - 400 m</td>
</tr>
<tr>
<td>U Carboniferous, NW Germany</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Martinius 1996</td>
<td>0.5 - 9 m</td>
<td>7 - 140 m</td>
</tr>
<tr>
<td>Tertiary, Spain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nami and Leeder 1978</td>
<td>3 - 8 m</td>
<td>35 - 280 m</td>
</tr>
<tr>
<td>M Jurassic, Yorkshire, England</td>
<td></td>
<td></td>
</tr>
<tr>
<td>North and Taylor 1996</td>
<td>1.5 - 8 m</td>
<td>30 - 370 m</td>
</tr>
<tr>
<td>Permian, Utah</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Platt and Keller 1992</td>
<td>2 - 6 m</td>
<td>50 - 600 m</td>
</tr>
<tr>
<td>Miocene, Switzerland</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Puigdefabregas and van Vliet 1978</td>
<td>1.5 - 2 m</td>
<td>175 - 400 m</td>
</tr>
<tr>
<td>Tertiary, N Spain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Robinson and McCabe 1997</td>
<td>0.5 - 18 m</td>
<td>3 - 1600 m</td>
</tr>
<tr>
<td>U Jurassic, S Utah</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stewart 1981</td>
<td>6 - 10 m</td>
<td>60 - 90 m</td>
</tr>
<tr>
<td>L Cretaceous, S England</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Van Veen 1994</td>
<td>2 - 10 m</td>
<td>13 - 495 m</td>
</tr>
<tr>
<td>U Oligocene, Loranca Basin, Spain</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The thickness-width data show a rather wide range and frequently significant scatter (e.g. Collinson 1978 and Robinson and McCabe 1997). However, the data sets are considered to provide a good basis for input and stochastic sampling in 3D geological computer modelling, the average width of the deposits seems not to exceed a few hundreds of metres. The scatter in the data may well be subject to
error in measurement, i.e. the true geometry of channel deposits exceeding the size of the outcrops.

Far less data are available for the downstream length of meander belt deposits, these vary between 'ten km to hundreds of kms' (Atkinson 1988), up to kms' (Stewart 1981), as well as only 100-400 m (North and Taylor 1996) and 32-230 m ( Cuevas Gozalo and Martinius 1993).

The length largely depend on the amount of sinuosity of the channels. Low- to medium-sinuosity channels may typically have more continuous downstream deposits, whereas pointbar deposits of high-sinuosity channels may have limited length. Another factor controlling the downstream connectivity of meander belt deposits is the abruptness of abandonment of the main water-transporting channel, i.e. the severity of clay plugging (Fig.80; Collinson 1978; Martinius 1996: Length ~ 1.4 x Width). These factors form a major uncertainty in modelling meander belt sandstones. Another major uncertainty is contained in the spatial distribution between the meander belt sands of which from literature no data has been found available to date.

Attempts have been made to analyse the orientation of the different types of channel sandstones (important for proper 3D modelling input) from oriented cores and borehole image logs. It is recognised that interpretation of fluvial crossbedding orientations data may be subject to error. In general, braided channel deposits are characterised by downstream accretion, however, also lateral accretion surfaces may be present, perpendicular to the palaeo-flow orientation. Furthermore, in meanderbelt deposits also palaeo-flow orientations are present besides lateral accretion.

In sequences where core data reveal the presence of braided channel deposits, dominant palaeo-flow towards west and northwest has been measured for the deposits in SE Drenthe. The major sedimentary dips obtained from sequences of meander belt sandstones have been interpreted to represent lateral accretion surfaces and these also indicate overall palaeo-flow to west and northwest, similar to the braided channel deposits.

Glover and Jones 1997 report dominant westward palaeo-flow in the U Carboniferous of NW Germany (with a source probably in the present-day Baltic area). This westward trend of fluvial systems may well have been guided by syn-sedimentary activity of the largely E-W trending Oesning and Gronau fault zones. Therefore, the Tubbergen Sandstone in SE Drenthe is interpreted to represent a westward continuation of the Carboniferous deposits present in NW Germany. The
W-NW palaeo-flow orientations as interpreted for SE Drenthe are in line with the overall flow pattern in W Germany. Syn-sedimentary activity of the Coevorden and Holsloot wrench fault zones may well have guided palaeo-flow orientation of the Carboniferous channel systems in SE Drenthe towards the NW (Fig.72). It is of interest to note that the Quaternary (!) Baltic River system (Tebbens, Kroonenberg and van den Berg 1995) had a westward orientation through W Germany and a NW orientation in NW Netherlands, which may well indicate as late as Quaternary activity of these major faults.

The Oesning and Gronau fault zones are known to have played a prominent role through time: off-platform Zechstein-1 and -3 carbonate build-ups occur in the Osnabrueck area (Paul 1995) and these developed most likely on palaeo-relief caused by the Oesning fault zone. The NW German Oesning fault zone approximately represents the northern boundary of the Variscan Rhenish Massif and it formed the southern limit of Rotliegend and Coppershale deposits, the southern edge of the Zechstein Basin, as well as the southern limit of the Lower Cretaceous Lower Saxony Basin (Ziegler 1989). Furthermore, the fault zone played a dominant role during Late Cretaceous inversion, resulting in e.g. Carboniferous outcrop, combined with magmatic rise (Bramsche and Vlotho Massifs in the Osnabrueck-South Oldenburg area in W Germany).

In addition to the westward palaeo-flow orientation in NW Germany (Glover and Jones 1997), Hampson, Elliot and Davies (1997) and Rippon (1997) report dominant eastward palaeo-flow in the U Carboniferous of the Pennine Basin, UK. Furthermore, Hampson, Stollhofen and Flint (1997) report dominant NW oriented palaeo-flow in the Ruhr area, Germany. Langenaeker and Dusar (1992) report dominant U Carboniferous palaeo-flow towards the north and northwest in the Campine Basin, Belgium. Hence, the overall palaeo-flow of the U Carboniferous fluvial systems in NW Europe appears to show a semi-radial character, directed towards the central North Sea area.

6.3 3D modelling of the Den Velde reservoir

The Upper Carboniferous Den Velde reservoir was discovered in 1986 and taken into production in 1995. Gas is produced from well DVD-1 (Fig.81). Well DVD-3 is producing from the overlying Zechstein 2 Carbonate reservoir. After ca. 1 year of production the reservoir pressure dropped by 150 bar (initial 325 bar), the production rates dropped from 500,000 m³/d to ca. 250,000 m³/d and a total
Carboniferous reservoirs

connected GIIP of only $0.4 \times 10^9$ m$^3$ to the well was measured from production data (compared to an initially calculated GIIP of $3.3 \times 10^9$ m$^3$). Because of this extremely anomalous production and connectivity, the Den Velde reservoir was chosen for study to resolve the background of the problems and to serve as a pilot for other anomalously behaving reservoirs in the SE Drenthe and Twente areas.

The Den Velde reservoir comprises U Carboniferous Tubbergen Sandstone sequences, with multi-storey braided channel sands at the base, overlain by meander belt sandstones and associated crevasse splay sands (Fig.74). Initial production test rates of well DVD-1 were dominantly from sand 4, a braided channel sand complex (Fig.82). The production test indicated the presence of a near-by flow boundary. Therefore not surprisingly, sand 4 showed rapid depletion and was producing only reduced amounts of gas after 1 year of production, whereas 50% of gas production was then obtained from sand 5 (Fig.82, also a braided channel sand complex but less porous than sand 4). The overlying sands 1, 2 and 3 (dominantly meandering channel and crevasse splay sands) were contributing only minor amounts to gas production.

To resolve the anomalous production and connectivity of the Den Velde reservoir, advanced 3D computer modelling was applied by means of the Geocap modelling package.

Conventional geological modelling and calculation of GIIP was previously restricted to 2D seismic depth maps, isopach maps, average porosities and gas saturations from well log data, complemented by a block diagram representing a conceptual reservoir model. Geocap enables subdividing the reservoir into a refined 3D model containing discrete volume cells (voxels, e.g. x, y, z: $100 \times 100 \times 0.5$ m), each being assigned a user-defined facies type and a specific porosity, permeability and saturation value (obtained from well data). The modelling package enables rapid assessment of GIIP calculations and static connectivity.

Initially, a full-correlation static model was established, i.e. fieldwide correlation of the braided channel as well as the overlying meander belt sands and applying average porosity and saturation data as obtained from wells data. This prior model indicated a fairly good match with the original expectation volumetric GIIP of ca. $3.3 \times 10^9$ m$^3$ together with a calculated, though unrealistic full connectivity (compared to a measured connectivity of only $0.4 \times 10^9$ m$^3$).
However, by modelling isolated, scattered meander belt sands in the upper half of the reservoir (i.e. modelling a stochastic, labyrinth-type reservoir based on the outcrop analogue data sets) and by generating a detailed porosity and saturation matrix (based on mercury capillary pressure measurements from cores), a reduced volumetric GIIP of ca. $2.8 \times 10^9$ m$^3$ was calculated. The reduction in volumetric GIIP of ca $0.5 \times 10^9$ m$^3$ is the result of modelling discontinuous labyrinthine-type meanderbelt sands in the upper part of the reservoir. Nevertheless, this model still indicated too high calculated static connectivity of ca. $2.6 \times 10^9$ m$^3$ (compared to the measured $0.4 \times 10^9$ m$^3$).

The prior model was validated by a novel technique, i.e. constraining the model by importing seismic inversion data into the Geocap modelling package. Increased computing power and improved algorithms enable inversion of seismic reflectivity data into acoustic impedance volumes and finally into reservoir properties like porosity and net sand thickness. For details of the seismic inversion technique reference is made to Duijndam (1988) and for an example of practical application reference is made to Burge and Neff (1998). The model, constrained by seismic inversion data, indicated a total volumetric GIIP of $2.6 \times 10^9$ m$^3$, fairly in line with the prior deterministic, partly isolated channel sand model. The seismic inversion data also indicated the presence and spatial distribution of individual, isolated meandering channel sands in the upper part of the model (Fig.83) containing ca $0.5 \times 10^9$ m$^3$. Also details from the laterally extensive braided channel sands in the lower part of the reservoir were visualised from the inverted seismic data (Fig.84). Nevertheless, the connectivity calculated from this seismically constrained model remained on the high side, as was the case with the prior model (ca. $2.4 \times 10^9$ m$^3$).

Preliminary interpretation of a recently acquired new 3D seismic survey in the area revealed indications of largely NW-SE oriented, deeper-seated intra-Carboniferous faulting. At reservoir level the seismic data are rather transparent and no clear faults could be detected. The orientations and location of these deep-seated fault zones are in reconciliation with indentations observed from seismic inversion volume data at the level of the laterally extensive braided channel sands (Fig.84).

By including such a possible sealing fault in the 3D models close to the location of well DVD-1, a full match with the measured connectivity was obtained (Fig.85A; ca. $0.4 \times 10^9$ m$^3$). Unconnected GIIP volumes of ca. $2 \times 10^9$ m$^3$ were identified in the northeastern part of the reservoir (Fig.85B), mainly contained in sands 3 and 4 (Fig.82), which package is probably furthermore separated by another fault further to the north (Fig.85B). A borehole image log obtained from well DVD-3 indicated...
the presence of NW-SE oriented, shear faults/fracture zones, in line with the productivity behaviour and the indentations observed in Figure 84.

Economic calculations do not warrant development of the limited GIIP of only $0.5 \times 10^9 \text{ m}^3$ contained within the isolated meanderbelt sands in the upper part of the reservoir by means of a horizontal well including a number of hydraulic fractures. Even technically it is not considered feasible that hydraulic fracturing could propagate through 15-25 m thick floodplain shale packages separating the isolated meanderbelt sands. Coals from the Osnabruce and S Oldenburg areas show vitrinite reflectance values of 2-6 %, indicating previous deep burial (> 5km) and/or overcooking due to granite intrusives (Bramsche and Vlotho Massives), resulting in overcooked, brittle floodplain shales. However, vitrinite reflectance values of only up to 1% are measured in the SE Drenthe area, indicating less mature shales, which are unlikely to allow propagation of hydraulic fractures of up to 30 metres.

A NNE oriented horizontal sidetrack of well DVD-1 is planned (Fig. 85A) to access the remaining unconnected reserves of ca. $2 \times 10^9 \text{ m}^3$ to the northeast of well DVD-1 (mainly contained in sands 3 and 4). The area consists of two isolated compartments separated by a sub-seismic fault. The well is designed to connect isolated compartments and to possibly penetrate additional, so far undepleted isolated meanderbelt sands in the upper part of the reservoir. Two hydraulic fracs are planned to interconnect both sands through the only 2-4 m thick shale separating these sands (Fig.82). The borehole image log of well DVD-3 revealed NE-SW oriented borehole breakouts, indicative of local NW-SE oriented present day maximum horizontal stress. Therefore hydraulic fracturing will propagate near-perpendicularly to the planned well. This pilot study has revealed the causes of the poor performance of the Den Velde reservoir: 1) a complex labyrinth-type character in the upper part of the reservoir, together with reduced reserves and 2) in addition, poor connectivity of the laterally extensive braided channel sands in the lower part of the reservoir due to fault compartmentalisation.

This study will act as a template for further studies for possibly accessing remaining reserves within a number of anomalously producing Carboniferous reservoirs in the NE Netherlands. The good match in GIIP between the prior deterministic and the seismic constrained model is expected to provide a unique opportunity for appraisal of so far un-drilled blocks of the SE Drenthe area, in which well planning may be based on the signature of seismic inversion data.
N.B. The GIIP figures as quoted in this chapter should be treated as tentative. A recently acquired new 3D seismic survey is being interpreted which will probably lead to a revision of the structural contour map at top Carboniferous and the fault pattern and hence to differences in GIIP calculations.
References


References


References


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At the conclusion of this thesis I wish to express my gratitude to my parents for enabling, supporting and stimulating me to finalise my studies. Furthermore, I wish to thank my wife Margaret for bearing with me and supporting me in the self-inflicted burden of compiling a thesis during valuable private hours, days, weeks, if not months, whilst having a family life and a demanding job in the oil industry.

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Curriculum vitae

The author was born on the 1st of November 1951 in Vlagtwedde, Netherlands. He received his secondary education (HBS-B) at the Rijks Hogere Burger School in Ter Apel from 1965 to 1970.

The author received his BSc degree of geology in 1974 at the University of Groningen and received his MSc degree of Geology in 1979 at the University of Leiden, with Clastic and Carbonate Sedimentology as the major subjects and Stratigraphy as subsidiary subject.

From 1980 till present he is employed by Shell International Exploration and Production, The Hague, Netherlands, during which period he held various positions in the following companies:


Current position: Reservoir-geological advisor in the Technical Expertise Department of NAM’s Business Unit Gas Land, actively involved in NAM wide and Shell Group wide research and technology development/dissemination. He initiates and participates in discussions with other oil companies, government authorities and universities concerning extramural research and coaching of student trainees. He has organised and guided numerous fieldtrips over the past years. Furthermore, he is chairman of the Royal Dutch Geological and Mining Society, Division North Netherlands (Koninklijk Nederlands Geologisch Mijnbouwkundig Genootschap, Afdeling Noord Nederland).

The articles contained in this thesis are the result of reservoir-geological research carried out in the period 1991-1993 and 1995-1998 during employment with NAM.
Fig.1: Overview of NAM operated gas fields in the on- and offshore Netherlands.
Fig. 2: NAM operated Rotliegend gas fields in the Central Offshore Netherlands.

Fig. 3: Cross-section illustrating development of small fields by drilling of highly deviated, extended-reach wells from existing infrastructures.
Fig. 4: Volumetric GIIP versus material balance GIIP.

Fig. 5: Block diagram showing the depositional setting of the Slochteren Sandstone and the different facies types.
Fig. 6: Data envelopes showing porosity-permeability relationships of the Upper Slochteren Sandstone in the K15 and L13 area. Note the differences between the facies types (1 and 2) and the effects of authigenic clays in the L13-SE area (1* and 2*).
1. Mainly aeolian dry sandflat and aeolian dune.
2. Mainly damp and wet sandflat, sheetflood and wadi.

Fig. 7: Comparison of well characteristics showing 'small field behaviour', in contrast to behaviour of larger fields. Note: 1) lateral variation in amount of prolific sand, creating regional compartments, 2) shales, restricting cross flow, creating stacked mini-reservoirs /stratigraphic compartments, 3) authigenic clays may further reduce cross flow into prolific sands. N.B. presence of faults may create discontinuity of prolific sands, creating fault compartments.
Fig. 8A: Distribution of prolific sand in the K15/L13 area (percentages of gross Upper Slochteren Sandstone).

Fig. 8B: Distribution of net/gross ratios in the K15/L13 area, largely reflecting the amount of shale layers in the Upper Slochteren Sandstone.
Fig. 9: Dipmeter log suite of the Upper Slochteren Sandstone in the K17 area showing the presence of individual (1) and stacked aeolian dunes (2). The slipface sands show dips of ca. 20 degrees to west and southwest.

Fig. 10: Structural sketch map of top Rotliegend, L13-East area showing the main fault trend striking NW-SE, together with some dextral displacement along these faults (arrows). Note the presence of reverse faults and the overall anastomosing, braided character of the remaining faults, typical for wrenching.
Fig. 11: Seismic attribute display of L13-FD showing in-field lineations, indicative of strike-slip faults, folds and reverse faults, related to dextral wrenching.
Fig. 12: Dipmeter log of well L13-11 (L13-FF field) showing a small (reverse) fault cutting the well. Additional evidence is provided by lineations on seismic attribute maps and fault picks from log correlations.

Fig. 13: Burial graphs of the K17 and K15/L13 areas showing different authigenic clay contents, reflecting different burial history.
Fig. 14A: Scanning Electron Microscope photograph of the ROSLU of well L13-9 (L13-FF field, field of view ca. 40 micrometre). Fibrous, authigenic illite clay minerals in pores and pore-throats, severely reducing permeability.

Fig. 14B: Distribution of illite/smectite versus kaolinite ratios in the Upper Slochteren Sandstone of the L13 area. (X-ray diffraction data of waterlaid sands, fraction smaller than 2 micrometre).
Fig.15: Logs of well L13-11 (L13-FF field, illite/smectite/chlorite, drilled with waterbased mud). Some of the potentially prolific layers (Kh profile) do not contribute to flow (PLT), because of mechanical blockage in cement filled washouts.

Fig.16: Logs of well L13-15 (L13-FJ field, illite/smectite). Potentially prolific zones (Kh profile) have been impaired by oilbased mud (test skin +23). Bulk of gas flow originates from a zone with open fractures (core evidence, cycle-skips on sonic logs and losses while drilling).
Fig. 17: Material balance data of the K15-FG reservoir, indicating a total connected gas volume of only $2.3 \times 10^9$ m$^3$ for both wells ($0.8 + 1.5 \times 10^9$ m$^3$) compared to an expected total field volume of $8 \times 10^9$ m$^3$. The curvature in the plot of well -101 probably indicates inflow of additional gas and not aquifer movement (ref. J.B. Stark in: Frikken and Stark 1992).
Fig. 18: Type log suites of Gamma Ray, Porosity and Production logs (PLT) of both K15-FG development wells, illustrating the strongly layered character and the dominant gas-flow from sands with porosities in excess of 15% (PLT signatures). Note the larger amount of prolific sands in the ROSLU 1 of well K15-FG-102 and the small fault cut-outs (discussed in the following chapter).

Fig. 19: RFT pressure data of the L13-FC and L13-FD fields.
Fig. 20: Material balance data of the L13-FD field.

Fig. 21: Material balance data of the L13-FD field.
Fig. 22: Structural contour map at top Rotliegend, K15-FG field, Central offshore Netherlands.

Fig. 23: Structural cross-section K15-FG area.
Fig. 24: Appearance of geological features on CBIL images as a function of dip angle, relative to the borehole axis.

Fig. 25: CBIL images showing alternation of centimetre thin shales (black), cemented patches (bright) and porous zones (yellow). The vertical, brown features are scrape-marks in the mud cake of the borehole wall, resulting from the drill string (diminishing across the tight streaks). The tadpoles reflect true structural dips. The red lines on the correlation image mark the interpreted bedding surfaces.
Fig. 26: CBIL images and core photograph for comparison, showing the presence of a small aeolian dune with foresets dipping southwest. Note the alternation of cemented streaks (bright yellow) and porous laminae (orange-yellow). The red lines on the correlation image mark the interpreted bedding surfaces.

Fig. 27: CBIL fracture analysis showing a set of conjugate fractures, resulting from historical stress anisotropy.
Fig. 28: Schematic representation of stress distributions related to dextral wrenching, resulting in the generation of strike-slip shear zones (faults and fractures), reverse faults and borehole break-outs (after Biddle & Christie-Blick 1985 and Hancock 1985). See text for discussion of features.

Fig. 29: Thin section photograph of a sub-vertical shear fracture in well K15-FG-102. The fracture fill consists of crushed framework grains and rock-flour (mylonite), creating an effective permeability barrier. Note the non-cemented matrix around the fracture.
Fig. 30: CBIL images showing a brecciated zone (black patches), indicative of a fault cutting the wellbore. The features dipping ca. 30 degrees to the south (also marked by the red lines on the correlation image) are interpreted to represent shear planes which are synthetics to the main fault plane. They are represented by tadpoles. The dip symbols represent shear fractures which were generated prior to this faulting event.

Fig. 31: Reconstruction of reverse faults cutting well K15-FG-102. The associated fault-drag and minor folding explains the anomalous northward structural dips. The fault planes and the subvertical shear fractures (dashed) severely hamper horizontal gas flow into the wellbore.
Fig.32: CBIL images showing borehole break-outs in black. The vertical feature on the amplitude display (brown at NW) represents a groove in the mud cake of the wellbore, made by the drill-string at the downside of the hole.

Fig.33: Rose diagram of borehole break-outs trending ENE-WSW, ascribed to the present-day stress anisotropy.
Fig. 34: 3D seismic Azidip map of top Rotliegend of the K15-FG field. Lineations are consistent with the deformation features, related to dextral wrenching. These lineations are interpreted to represent partly to completely sealing strike-slip faults or shear zones. The location of a recently drilled third development well is indicated by the black dot to the southwest of K15-FG-101 (see text for discussion of well results).
Fig. 35: Top Rotliegend structural map L13-FE field, Central Offshore Netherlands, showing the abandoned discovery well L13-8 and development wells L13-FE-102 and L13-FE-103.

Fig. 36: Material balance data of the L13-FE field. Wells L13-FE-102 and -103 were expected to connect the field's reserves.
Fig.37: Type log suite of Gamma Ray, Porosity and Production Logging (PLT) illustrating the difference in flow characteristics between L13-FE wells. Layers with porosities in excess of 15% dominate the flow into the well bore (PLT signatures).

Fig.38: Porosity-permeability cross-plots of core data showing the difference in amounts of highly permeable layers (porosity >15%) in the Upper Slochteren Sandstone (K15 East: K15-FA and -FG fields and L13 East: L13-FE and -FG fields, Fig.2).
Fig. 39: Top Rotliegend 3D seismic Azidip map L13-FE field. The mainly N-S trending, en echelon lineations (purple) are interpreted to represent sealing strike-slip faults. The other lineations represent predominantly normal faults with distinct vertical offsets.
Fig. 40: Cross-section of the L13-FE field showing the planned sub-horizontal trajectory, the relatively complicated overburden and the presence of strike-slip faults (vertical exaggeration 2x).

Fig. 41: Analysis of expected influence on inflow performance for the sidetrack. See text for discussion of features.
Fig. 42: Results of drilling mud impairment tests on core samples. The highly permeable aeolian sands are more severely affected by oil based mud (IOEM) than the less permeable waterlaid sands.
Fig. 43: Uncertainty in evaluating the Zechstein overburden stratigraphy of the sidetrack by means of the Gamma Ray-Measurement While Drilling technique.
Fig.44: Well trajectories in plan view and cross section of hole 1 and 2 of the sub-horizontal sidetrack showing considerable dog-legs (vertical exaggeration of cross section 2x).

Fig.45: Cross-section of the Upper Slochteren Sandstone showing the isolated position of prolific sands in the original well -102, the significant amount of prolific sands encountered by the sidetrack and the presence of a strike-slip fault in the middle of the trajectory. The black triangle indicates the slotted liner shoe (vertical exaggeration 3x).
Fig.46: The effect of a small scissor-type fault on apparent reservoir thickness.

Fig.47: Three-dimensional, structurally unconstrained reservoir-geological (MONARCH) model of the Upper Slochteren Sandstone of the entire L13 East area (11 x 10 km, vertical exaggeration 60x, view from SW). Prolific sands: yellow; shales: blue; poor quality sands: transparent. Note the prolific sands showing a decrease in quantity and a more scattered nature towards the east (L13-FE area).
Fig. 48a: Above: Aerial photograph of merged barchan dunes (foreground) and individual ones (background), migrating on a sandy sabkha interdune area (southern part of the Emirate of Qatar). The lateral extent and preservation potential of such dunes is generally rather low.

b) Below: Tidal flats (dark) intersected by tidal channels in a playa lake margin setting (eastern part of the Emirate of Qatar). An encroaching blanket of aeolian sand gradually covers the system (arrow). Such sands may well be preserved by rapid playa lake transgressions and deposition of shales, as observed from reservoirs in the NE Netherlands.
the Netherlands (GR, porosity log and seismic trace of well Münsterzell-1 passed).

Lith., which provides an excellent analogue for the Keokukian Sandstone reservoirs of

Fig. 4.9: Outcrop photograph of accretion and fluvial deposits of the Permian Cutter Group,
Fig.50: Gas fields in the NE Netherlands: ZEZ2C reservoirs highlighted.
Fig. 51: Facies distribution map of the ZE2C in SE Drenthe and Twente.

Fig. 52: Productivities of individual ZE2C wells (Q50: test productivity at 50 bar drawdown). Very poor productivities from wells in tight, basinal to distal slope carbonates without open fractures (insert: well 1). Increasing productivities from wells in more porous, proximal slope to platform carbonates and wells, including (sub)horizontal, that encountered open fracture systems, which provide an interconnected network (insert: well 2).
Fig. 53A: Crossing fracture pattern as frequently observed in cores of the ZEZ2C, previously interpreted as the result of overburden loading. However, the accommodation space problem at the intersection of fractures is inconsistent with the inferred origin.

Fig. 53B: Alternative explanation, involving horizontal stress anisotropy as a result of wrench tectonics: N-S oriented, horizontal compression and related E-W extension, resulting in an apparent horst and graben configuration (Frikken 1996c).
Fig. 54: Dip-map of top ZE2C (abbreviations like e.g. OSH and EMM relate to the reservoirs Oosterhesselen and Emmen in Figure 50). En-echelon left-stepping Riedel faults, pull-apart basins and rhomboidal fault patterns characteristic of dextral wrenching. Insert: Plan view strain ellipsoid showing deformation features related to dextral wrenching (after Hancock 1985, Biddle and Christie-Blick 1985).
Fig. 55: Dip-map of the Jurassic Base Altena in the SE Drenthe area (for reference: the southeastern part of Fig. 54). *En-echelon* right-stepping Riedel faults along the major Holstoot fault zone, indicative of NNE-SSW oriented sinistral wrenching. Associated E-W oriented dextral wrenching in the Emmen and Schoonebeek areas as indicated by *en-echelon* left-stepping Riedels.
Fig.56A: Dip map of Base Altena in the Emmen area (detail of Fig.55) showing E-W oriented *en-echelon* synthetic Riedels (pull-apart) as a result of dextral wrenching (scale in metres).

Fig.56B: Three-dimensional visualisation (Shell proprietary Geocap modelling software) of Base Altena in the greater Emmen area showing folding up to 1400 metres throw (grid cells: 200x200 m).
Fig. 56C: Structural contour map at top Rotliegend of the Munnekezijl area (Fig. 50; MKZ in Fig. 54) showing dextral offset of antithetic Riedel faults of up to 750 m to the southeast of the reservoir.

Fig. 56D: Time map at base Zechstein from the central part of the Lauwerszee Trough (detail of Fig. 54) showing a pull-apart graben of ca. 2 kms along an antithetic Riedel fault (depth scale in metres).
Figure 25E: Core photograph of a Carboniferous fluvial channel sandstone with angular cross-cutting fractures forming a fault plane. Figure 26A illustrates a plan view expression of these fracture sets at Jurassic shallowwater levels, indicative of continued wrench tectonics through time. The map in figure 26B shows shallow water structures and reverse faulting pop-ups at Carboniferous level and at the Permian level (figs 26C and 26D).
Fig. 57: Dip-map of Base Tertiary. *En-echelon* left-stepping synthetic Riedel faults along the major fault systems, indicative of dextral wrenching. The ones along the W Groningen fault zones are of special interest because of their characteristic sigmoidal geometry.
Fig. 58: 3D seismic N-S section of the Coevorden area showing a significant pop-up structure at top Carboniferous, indicative of wrench tectonic deformation.

Fig. 59: Sketch map of the ZE2C reservoirs in SE Drenthe showing the main wrench fault trends and E-W oriented reverse faults, characteristic for dominant N-S compression from NW-SE oriented wrenching in the area. Note the reverse faults in the Coevorden area, which are offset by synthetic and antithetic Riedels (for legend see Fig. 54).
Fig.60: Rose diagrams of fracture strike orientations from all ZEZ2C cores and borehole imaging logs in the SE Drenthe area. The fractures show three distinct populations (Fig.60A) of which the orientations are in line with wrench tectonic deformation features (for legend see Fig.54). Orientation of open fractures indicates origin as extensional fractures or antithetic Riedel shear fractures.

Fig.61: Rose diagram of hydraulic fracture strike orientation of the Slochteren Sandstone in well BLF-104, NE Netherlands, indicative of the orientation of the present-day horizontal maximum principal stress (fracture orientation measured by means of downhole geophones. The smaller additional spikes may be indicative of conjugate Riedels.
B) Outcrop of the Carboniferous Ross Sandstone SW Ireland.
A) Dip map at top Holmberg of the Lauwersse Trough, NE Netherlands.
(Riedel's) For comparison see figures 6C and D.

Figure 62A/B: Large and medium-scale examples of parallel wrench faults with associated near-parallel cutter faults/creepers (tectonic extensional and/or strike-slip)
Fig. 62C/D: Small and large-scale examples of parallel wrench faults and associated near-perpendicular faults/fractures. For comparison see figures 62A and B.

C) Outcrop of carbonates of the Carboniferous Paradox Formation, SE Utah (lighter for scale).

D) Aerial photograph of fault patterns in the southeastern Tibesti Mountains, Chad (scale 1: 35,000). The strike of fault systems is accentuated by fluvial channels. Although only one major fault system is shown, the parallel faults perpendicular to it show a very regular spacing of ca. 250 metres. Source of photo unknown; original caption: "Beispiel eines Flusznetszes bedingt durch Klueffe, die die flachliegenden Sandsteine durchziehen. Es finden sich auch paralleler Fluszausrichtungen, ebenfalls klueftungsbedingt, Photo I.G.N."
Fig. 63: A) Wrench tectonic deformation features, Carboniferous Ross Sandstone, SW Ireland. Fractures, probably extensional (E) and/or antithetic Riedel shears (R'), occur at a fairly regular spacing of 0.5-1 m and are near-perpendicular to the major dextral wrench faults (DW, 7-10 m apart). The density of fractures increases towards the wrench faults.

B) Comparison with the Emmen field (top ZEZZC) showing a similar configuration of E-W dextral wrench faults. Note the location of a recently drilled E-W horizontal sidetrack of well EMM-8 in the central part of the field, which encountered a major open fracture system.
Fig. 64: CBIL borehole image of the ZEZ2C in well COV-10 (near-vertical) showing a ca. 1 m open fracture/fault zone (black). Gamma Ray and Caliper log readings confirm the open nature of the fracture/fault. The feature dips at an angle of 80 degrees to the east and therefore strikes N-S.
Fig. 65: Outcrop examples of *en echelon* synthetic Riedel shear fractures (R) occurring at acute angles to the main wrench faults and restricted to the vicinity of the faults (details of figure 13). The Riedels cross-cut the main wrench faults and are therefore younger of age.

A) Carboniferous Ross Sandstone, SW Ireland: left-stepping, indicative of dextral wrenching.

B) Carboniferous Paradox formation, SE Utah: right-stepping, indicative of sinistral wrenching. Comparable to the left-stepping synthetic Riedels Figure 54 and Figure 57.
Fig. 66: Illumination dip-map (top ZE22C) of the central part of the Emmen field (the area of EMM-8 horizontal sidetrack). NNW-SSE striking lineations (pink and black, artificial illumination from NE) may represent zones of major open fractures and/or open shear faults. The orientation is in line with the open fractures from the Emmen cores.
Fig. 67: Time map at top Carboniferous showing a rhomboidal fault pattern, which are well known from the subsurface of the Netherlands. Such patterns occur in areas where major wrench fault systems branch. The pattern is interpreted to represent a conjugate set of Riedel faults, associated with E-W oriented dextral wrenching.
Fig. 68A: Outcrop of Precambrian sandstones in Brittany, France: deformation features resulting from dextral wrenching, representing a small-scale analogue for the frequently rhomboidal fault patterns at top Carboniferous level in the subsurface of the Netherlands.

Fig. 68B: A similar outcrop analogue as in Figure 68A: Carboniferous Ross sandstone, SW Ireland.
Fig. 69: Outcrop examples of compressional deformation features related to wrenching.
A) Reverse fault (throw ca. 1.5 m) in Precambrian sandstones in Brittany, France.
B) Folding with thrusting and back-thrusting in the Jurassic Summerville Formation, SE Utah.
Such deformation features probably generated palaeo-highs during Zechstein times in the Netherlands, triggering the growth of carbonate build-ups.
Fig.70: Basal Zechstein isochron map (detail of Figure 67) showing a dominantly NE-SW striking anomaly (arrow, blue: thickening in time), indicative of a possible carbonate build-up (triggered by a Late Carboniferous palaeo-high). The feature is in line with the orientation of the reverse fault/fold trend from E-W wrenching (strain ellipsoid in Fig.67). Note the rhomboidal fault pattern. Black colour represents poor seismic data quality.
Fig. 71: NW-SE seismic section across the anomaly in Figure 70, showing a possible porous ZEZ1C carbonate build-up as indicated by an additional red loop.

Below: Photograph of the ZEZ1C Pinsenberg Reef complex near Kroelpa in Thuringia, Germany. This fringing carbonate build-up has dimensions comparable to the one shown in Figure 70 and above: 4 x 0.5 km and ca. 100 m thick.
Fig. 72: Overview of the Carboniferous reservoirs in the NE Netherlands (dark grey). Overall higher recovery factors, interpreted to may well be the result of better sand development due syn-sedimentary faulting along the Coevorden-Holsloot wrench faults (for location see Figure 57).
Fig. 73: Gamma Ray log correlation of part of the Tubbergen Sandstone of the Coevorden area. Pronounced, stacked channel deposits (higher n/g) grading into a low n/g area (no fault cut-out evident) across only 400 m, indicative of syn-sedimentary faulting.

![Gamma Ray log correlation](image)

Fig. 74: Type log suite of the Tubbergen Sandstone well Den Velde-2 showing two sequences starting with highly productive, stacked braided channel sands, often overlying coals (peaks on FDC log), grading upwards into less productive, probably isolated meandering channel deposits with poor connectivity.

![Type log suite](image)
Fig. 75A: Overview of Lower Westphalian D deposits in the Piesberg Quarry north of Osnabrueck, NW Germany (height ca. 80 m, view near-perpendicular to palaeo-flow). Two sequences, starting with multi-storey, braided channel deposits (downstream accretion-dominated), changing upwards into laterally less persistent meandering channel deposits (me, lateral accretion-dominated). Note the meandering channel abandonment clay-plug (arrow), the occurrence of thicker floodplain shales (uppermost part) and the thin coal layers (black).

Fig. 75B: Overview of Lower Westphalian D deposits in the Niederbockraderen Quarry, west of Osnabrueck, NW Germany (height ca. 40 m, view near-parallel to palaeo-flow). Lateral accretion meander belt (highlighted) and crevasse splay deposits embedded in floodplain shales and silts, i.e. well-drained palaeosols. This section is probably equivalent to the uppermost part of the section in figure 75A.
Fig.76: Stacked, multi-storey fluvial sandstones of the E Palaeocene Tremp Formation, N Spain (ca. 25 m thick, section near-perpendicular to the palaeo-flow), consisting mainly of braided channel deposits (dominantly downstream and minor lateral accretion).

Fig.77: Conceptual drawing of single-storey, isolated, ephemeral meandering channel deposits (lateral accretion) forming a labyrinth-type reservoir. Tertiary of the southern Pyrenees (Puigedefabregas and van Vliet 1978, for dimensions see text).
Fig. 78: Single-storey, isolated lateral accretion deposits of an ephemeral meandering channel system (ca. 5 m. thick, width ca. 40 m., view perpendicular to palaeo-flow). Middle Jurassic Scalby Fm., Yorkshire, England. Channel abandonment characterised by a clay plug. Colleague for scale at left. For dimensions see text (Nami and Leeder 1978).

Fig. 79: Individual lateral accretion sand layers (1-2 m thick) separated by shales (lower half of photograph). These deposits reflect large fluctuations in water-discharge, shales deposited from suspension during temporary drops in discharge/sand-supply. Ephemeral meandering river system of the Triassic Chinle Formation near Moab, Utah, view near-perpendicular to palaeo-flow.
The amount of abandonment abandoned
By clay-plugs from oxbow lakes and from abandoned channel
Pointbar deposits (these range in width between 200 - 800 m) may be disconnected
Fig. 8.0 Conceptual plan view of a meandering channel system illustrating the

scroll bar
Pointbar deposits
Crevasse
Abandoned channel fill
Water transporting stream
Fig. 81: Structural contour map of top Carboniferous of the Den Velde reservoir (Figure 72 for location).

Fig. 82: Log suite of the Tubbergen Sandstone of well DVD-1. Production logs (PLTs) show dominant contribution in time from sands 4 and 5 (braided channel sands), whereas only a minor contribution is obtained from sands 1-3 (meandering channel and crevasse splay sands).
Different colours applied to individual bodies, floodplain shales transparent (view largely to the west and north west, in line with the palaeo-currents from cores and logs. sand bodies (within up to 400 m) with varying inter-connectedness, the orientation is indicating the presence and spatial distribution of isolated pools and crevasse spits.

Fig 8.3: Seismic inversion volume of the uppermost part of the Den Veldde Reservoir.
Fig. 84: 3D Geocap visualisation based on seismic inversion data. Volume body representing the top part of a fieldwide extensive braided channel sand complex (lower part of the Den Velde reservoir, sand 4, Fig 82). Note the two indentations in the body, probably representing decreased porosity due to the presence of strike-slip fault zones (well DVD-1 shown, view from south, individual cells 100x100 m).
Fig.85A: Plan view Geocap visualisation of the Den Velde reservoir showing reduced connected GIIP contained in an isolated fault block around well DVD-1 (in red). A planned horizontal sidetrack of the well is shown in yellow.

Fig.85B: Same as above, showing GIIP (isolated from DVD-1) mainly contained in braided channel sands in the lower part of the reservoir (wells DVD-1 and -3 shown in red). The volume is probably further subdivided by an additional sub-seismic fault in the central part of the reservoir.