NAM

On the implementation of Sedimentological data in Porosity Modelling for the Groningen field

Clemens Visser, Richard Porter and Jose Solano Viota

Date November 2016

Editors Jan van Elk & Dirk Doornhof

General Introduction

Sedimentology studies the properties of sedimentary rocks such as sandstones, siltstones and claystones, and the processes leading to their formation. These processes are erosion and weathering, transport, deposition and diagenesis. In constructing a model of the Groningen Rotliegend reservoir, sedimentology can provide a consistent framework for the 3-D distribution of reservoir properties such as porosity, permeability and clay content.

This report investigates the relation between sedimentological characteristics and reservoir properties in core material from the Groningen field. This can lead to an improved reservoir model. As the compaction of the reservoir in response to a pressure decrease is dependent on porosity, this study is also very relevant for the prediction of field-wide compaction and subsidence.

This report is therefore important for both geology studies and reservoir engineering studies (Ref. 1 to 5).

References

1. Petrographic study of well Zeerijp-3A (ZRP-3A) Final Report, Panterra Consultants, November 2016.
2. Petrographic Aspects of the Rotliegend of the Groningen field Inventory and quick-look analysis of petrographic data from the Groningen field, Nederlandse Aardolie Maatschappij B.V. (Clemens Visser), November 2016
3. Groningen Field Review 2015 Subsurface Dynamic Modelling Report, Burkitov, Ulan, Van Oeveren, Henk, Valvatne, Per, May 2016.
4. Independent Review of Groningen Subsurface Modelling Update for Winningsplan 2016, SGS Horizon, July 2016.
5. Technical Addendum to the Winningsplan Groningen 2016 - Production, Subsidence, Induced Earthquakes and Seismic Hazard and Risk Assessment in the Groningen Field, PART I – Summary and Production, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), 1st April 2016.

NAM

<table>
<tr><td rowspan="2">Title</td><td colspan="2" rowspan="2">On the implementation of Sedimentological data in Porosity Modelling for the Groningen field</td><td>Date</td><td>November 2016</td></tr>
<tr><td>Initiator</td><td>NAM</td></tr>
<tr><td>Autor(s)</td><td>Clemens Visser, Richard Porter and Jose Solano Viota</td><td>Editors</td><td colspan="2">Clemens Visser, Jan van Elk
Dirk Doornhof</td></tr>
<tr><td>Organisation</td><td>NAM</td><td>Organisation</td><td colspan="2">NAM</td></tr>
<tr><td>Place in the Study and Data Acquisition Plan</td><td colspan="4"><u>Study Theme:</u> Groningen Reservoir Model
<u>Comment:</u>
Sedimentology studies the properties of sedimentary rocks such as sandstones, siltstones and claystones, and the processes leading to their formation. These processes are erosion and weathering, transport, deposition and diagenesis. In constructing a model of the Groningen Rotliegend reservoir, sedimentology can provide a consistent framework for the 3-D distribution of reservoir properties such as porosity, permeability and clay content.

This report investigates the relation between sedimentological characteristics and reservoir properties in core material from the Groningen field. This can lead to an improved reservoir model. As the compaction of the reservoir in response to a pressure decrease is dependent on porosity, this study is also very relevant for the prediction of field-wide compaction and subsidence.

This report is therefore important for both geology studies and reservoir engineering studies (Ref. 1 to 5).</td></tr>
<tr><td>Directliy linked research</td><td colspan="4">(1) Geology of the Groningen gas field.
(2) Subsidence and compaction studies.
(3) Studies on the core acquired in well Zeerijp-3A (ZRP-3A)</td></tr>
<tr><td>Used data</td><td colspan="4"></td></tr>
<tr><td>Associated organisation</td><td colspan="4">NAM</td></tr>
<tr><td>Assurance</td><td colspan="4"></td></tr>
</table>

On the implementation of sedimentological data in porosity modelling for the Groningen field

Clemens Visser, Richard Porter and Jose Solano Viota

NAM, August 2016

Doc. No. EP201609201569

Summary

This study investigates the feasibility of using a facies model in support of constructing a reservoir model of the Groningen field. This builds on the premise that primary depositional features such as grain size, sorting and clay content are important controls on the reservoir quality of a sedimentary deposit. A 3-D representation of the distribution of lithofacies can then be used as a proxy for, e.g., the distribution of porosity and permeability.

The approach has been to revisit vintage core descriptions of an extensive selection of cored wells from the Groningen field, and reinterpret these on the basis of a consistent and fit-for-purpose lithofacies scheme. This allowed for the grouping of available routine core analysis data per lithofacies to check for trends and relationships. Special emphasis has been on the comparison between purely aeolian lithofacies and other sandstone types, because close to 80% of the available Groningen core material consists of sandstones.

Distributions of porosity and permeability data for different lithofacies are seen to largely overlap. Consequently, aeolian lithofacies cannot be distinguished from other sandstones on the basis of reservoir properties alone. This is explained from the observation that the Groningen sediments have been subjected to repeated reworking by fluvial and aeolian processes, leading to a diffuse distribution of reservoir properties. It is concluded that the facies modelling approach cannot serve to build more realistic reservoir property models. Nevertheless, geological understanding used in this study and that of others, should always be used when trying to refine the distribution of reservoir properties with other methodologies.

Table of contents

1. Introduction

The porosity distribution in the Slochteren reservoir sandstone of the Groningen field plays an important role in several ways. First, it provides the space for hydrocarbon molecules to accumulate, and therefore exerts a control on the total volume of gas that was initially in place, *i.e.* prior to the start of production. Second, the extraction of gas from the reservoir leads to reservoir compaction, which plays a role in the generation of induced seismicity. There is a direct relation between porosity and compaction (Ref. 1), be it that this relation is not yet fully understood. Understanding both the distribution of gas over the extent of the reservoir and the potential compaction that can take place require a detailed knowledge of the porosity distribution in the reservoir.

Models for describing the 3-D distribution of porosity are based on wireline log measurements at well locations. A porosity property is usually derived from density or sonic velocity measurements that are calibrated with direct measurements of porosity on core plugs. The porosity distribution away from the well locations is modelled by applying a mathematical interpolation algorithm. Advanced interpolation algorithms can be conditioned with a priori geological or geophysical information from different sources to assure that geologically realistic results are created.

The static model from the 2012 Groningen Field Review (GFR2012, Ref.2) applied porosity maps to steer the interpolation algorithms. These porosity maps were again based on wireline log measurements, hence on information from well locations only. A priori geological information was incorporated to a limited extent, by visually inspecting if trends in the porosity maps were in agreement with the general depositional model for the Slochteren Sandstone in the Groningen area.

The current study investigates options for exerting a more extensive control on the distribution of porosity by means of a facies model. The basic principle is that primary depositional features such as grain size, sorting and clay content determine the initial porosity of a sedimentary deposit, but also are an important factor in the reduction of porosity by compaction and diagenesis during burial. Primary depositional features are a function of the transporting medium (water or wind/air) and the energy of the depositional process. For example, transport of sand grains by wind action results in well-sorted clay-free sediments with high primary porosity. Fluvial (river) deposits tend to consist of a larger range of grain sizes and intermixed or interlaminated clay-size material, with consequently lower porosities. Depositional features and processes can be inferred from the description and interpretation of core material. Cored intervals can be divided into a number of lithofacies where each lithofacies comprises a distinct suite of textural parameters and sedimentary structures. The 3-D distribution of lithofacies is described by a facies model. Such a model incorporates information from all cored wells. Interpolation between the cored well locations is steered by depositional models which are derived from analogues (outcrop, recent, reservoirs). A lithofacies-based reservoir modeling approach can be successful when each lithofacies type has a distinct suite of reservoir properties, such that the 3-D distribution of lithofacies is a proxy for the distribution of, for example, porosity.

This document describes the efforts put into building a consistent and adequate facies model for the Groningen field, and the characterization of lithofacies in terms of reservoir properties, particularly porosity and permeability.

2. History of sedimentological investigations on Rotliegend core from the Groningen field

The first sedimentological study on Rotliegend core from the Groningen area was issued by Oomkens in 1964 (Figure 1, taken from Ref. 3). He proposed a threefold stratigraphic subdivision, as follows:

- Lower Slochteren formation: alluvial fan and floodplain deposition under semi-arid conditions on a coastal plain
- Upper Slochteren formation: dominantly aeolian sandstone derived from the underlying Lower Slochteren sediments with a dominantly westward transport direction,
- Ten Boer formation: claystones and siltstones deposited in low-relief areas which were intermittently flooded by sea water.

A subsequent study by Glennie (Ref. 4) on recent sediments in the Libyan desert confirmed earlier interpretations and stressed the importance of mixed fluvial and aeolian processes in a desert environment. The interpretation for the Ten Boer formation and distal, finer-grained Slochteren sediments changed from a marine coastal setting to a sabkha to lacustrine or playa lake depositional setting.

The next comprehensive sedimentological account of Groningen core material was published by Nicholls *et al.* (Ref. 5). This work involved detailed logging of core from 13 wells at 1:40 scale and less detailed description at 1:1000 scale of 23 additional cored wells. The objective was to develop a lithofacies scheme and provide core information in a form that can be readily applied to static reservoir modelling. The study distinguishes 10 different lithofacies, based on combinations of dominant grain size and sedimentary structures. These lithofacies were interpreted to have been deposited in five subenvironments within a desert basin setting: alluvial fans, braided streams, upper desert/outwash plan, lower desert/outwash plan and desert lake (Figure 2).

Cohen (Ref. 6) carried out a reservoir geological study of the Ten Boer Claystone in the Groningen area. Detailed core descriptions were available from 22 wells in the north and northeast of the field. He distinguished three main lithologies sand, silt and mud, and nine lithofacies based on a combination of a dominant and a secondary lithology (silty sand, muddy silt, etcetera). The desert lake depositional setting follows the context of Nicholl's study described above. The nine lithofacies types were deposited in four depositional subenvironments of the desert lake, of which aeolian flat is by far the most abundant. The dominant depositional process is adhesion of wind-blown sand and silt on a wet mudflat surface. Aeolian flat deposits are interbedded with rare and thin fluvial, lacustrine and aeolian beds.

The next step forward in terms of Rotliegend sedimentology was introduced by Reijers & Kosters (Ref. 7). This work was carried out in the framework of a regional Rotliegend Task Force study program, which also included modules on petrophysics, geochemistry, diagenesis and basin analysis. The sedimentology module included detailed logging of core from 27 wells from the Dutch onshore and offshore areas. The core descriptions and interpretations largely followed the work of Nicholls and Cohen (Refs 5 & 6). However, two new developments were introduced. One was a standardized Rotliegend lithofacies scheme with new terminology which was intended to be applied to all Rotliegend core from the entire Southern Permian basin (Ref. 7, and Figure 3). The other was the introduction of a computer-based core logging methodology.

The new Rotliegend lithofacies scheme comprised 16 different lithofacies, based on a combination of textural parameters and sedimentary structures. Combinations of genetically linked lithofacies are interpreted in terms of depositional (sub-)environment, as follows:

Aeolian setting:

- Aeolian dune
- Aeolian dry sandflat (groundwater table below depositional surface)
- Aeolian damp sandflat (groundwater table close to depositional surface)
- Aeolian wet sandflat (groundwater table at or above depositional surface)
- Aeolian mudflat
- Aeolian pond or lake

Fluvial setting:

- Fluvial sheetflood
- Channelized fluvial stream deposits
- Fluvial pond

The computer-aided core logging allows for recording of rock characteristics in ASCII files. The software creates output that can be displayed in spreadsheet format as a listing of depth intervals with a minimum thickness of 5 cm (and for some wells even down to 1 – 2 cm). A new row is created whenever one of the recorded parameters (grain size, clay content, structure, and so on) is changing (Figure 4). This digital format enables the import of lithofacies information into reservoir modelling software (Petrel) for comparison with data from other sources, such as wireline logs and core analysis data. It can also be loaded in drafting software to create graphical representations of the core descriptions.
Computer-aided core logging is now the standard approach. A large part of the vintage hand-drafted Groningen core descriptions has been revisited and converted into a digital format (add Table with core database).

The lithofacies (association) scheme introduced by Reijers *et al.* is still in use at NAM for description and interpretation of Rotliegend core. Later sedimentological work has had less focus on the description and interpretation of lithofacies, but rather on understanding the vertical variations and trends for correlation and reservoir zonation purposes (e.g., Refs 9, 10, 11). The concept is that the variability observed in wetter and drier lithofacies is driven by climatic variations. These variations must have taken place over the entire extent of the Southern Permian Basin. Climatic variations are cyclic in nature, particularly at the larger scale where they are driven by cyclic astronomical or orbital movements. Understanding this cyclicity and recognizing it in the rock record can provide a basis for correlation in an otherwise completely barren depositional environment. This is particularly so when used in combination with sequence stratigraphic concepts. The combined effect of variations in climate (fluvial run-off, lake expansion, wind activity), sediment supply and accommodation space exerts a major control on the 3-D reservoir architecture and lithofacies distribution of the Groningen field. These insights have successfully been applied in the construction of static models for Groningen since the GFR2012 (Ref. 2).

3. Current sedimentological review

As stated in the introduction, the objective of the current study is to investigate the feasibility of using a facies model to steer property distributions in the Groningen static model. Starting point was the database of digital (AppleCore) core descriptions already available for most of the cores (see example from well MWD-1 shown in Figure 4). However, this data set has two important drawbacks. First, the level of detail is very high, and too much overlap of reservoir properties between different facies can be observed. This is illustrated in Figure 5 taken from the 2003 field review (Ref. 12), showing an overview of core plug measurements grouped by lithofacies. This led to the decision not to follow a facies-based property modelling approach in the Groningen field reviews of 2003 and 2012. Second, the standardized core description scheme was implemented by different representatives from several contractor companies. This has resulted in apparent inconsistencies, which in cases makes it difficult to compare descriptions from different wells.
An additional drawback is that lithofacies cannot be converted into electrofacies, because their log responses also show significant overlap (Ref. 12).

The GFR2012 static model included a simplified electrofacies approach with a threefold subdivision into conglomerates, sandstones and claystones. However, since the Groningen reservoir rock is strongly dominated by the sandstone facies, this yielded insufficient granularity for a meaningful facies-based property modelling workflow. It was only used to define different porosity-permeability relations for each electrofacies.

The current attempt aims to overcome the drawbacks and issues mentioned above. A simplified version of the Rotliegend lithofacies scheme was developed by taking the threefold facies scheme from 2012 as a basis, but refining it where possible and potentially meaningful. This resulted in the following lithofacies scheme (also see Figure 6 and compare with Figure 3):

Conglomerate undifferentiated, code C
Extraclast Conglomerate, code CE
Intraclast Conglomerate, code CI

Pebbly Sandstone undifferentiated, code P
Extraclast-dominated Pebbly Sandstone, code PE
Intraclast-dominated Pebbly Sandstone, code PI
Aeolian Sandstone, code A
Sandstone (other), code S
Mudstone, code M

Special attention was paid to the sandstone lithofacies. Approximately 65% of the Rotliegend interval in the Groningen area consists of sandstone, 25% is mudstone and 10% is conglomerate. The sandstone proportion is even larger when the Ten Boer Claystone is not considered. A subdivision into different types of sandstone could possibly lead to a refinement of the facies-based modelling approach. Therefore, it was decided to try and distinguish between purely aeolian sandstones (code A) and undifferentiated sandstone (code S). The rationale for this is given by the general expectation that aeolian deposits are easy to identify and tend to have excellent reservoir properties because of their high degree of sorting. Code S consists of non-aeolian sandstones and sandstones where an aeolian depositional process could not unequivocally be established.

The vintage core descriptions from 20 wells were revisited at a 1 - 2 centimeter resolution, and converted into the above lithofacies scheme. All the work was carried out by the same skilled sedimentologist to ensure maximum consistency between the wells. The quality control and/or new classification was done with the use of the core photograph database, but with extensive checking on the core itself when photographs did not reveal sufficient detail. The study wells were selected on the basis of available core length and show a good spread over the Groningen field area (see map of Figure 7).

The resulting simplified lithofacies listings per cored well were loaded into Petrel as discrete facies logs ("Rich Facies" – after the author Richard Porter). Figure 8 shows an example correlation panel for wells Sappemeer-1, Stedum-1 and Uithuizermeeden-1, where the Rich Facies log forms the far-right column of each constituent well plot. The overall distribution of lithofacies in the 20 studied cores is given in the histogram of Figure 9. Sandstones comprise 69.4% of the core material, mudstones 21.0%, and conglomerates and pebbly sandstones 9.7%. This composition compares well with the overall Rotliegend composition mentioned above. Noticeably, there is a fairly good match between the Rich Facies log and the electrofacies log.

The dominance of sandstones is as expected, but the proportion of purely aeolian sandstone (Code A) seems to be quite low. This requires further explanation (see section on discussion of results).

4. Cross-plotting porosity/permeability data per facies type

4.1 Introduction

The reservoir quality of the lithofacies types is evaluated on the basis of a series of cross-plots of core plug measurements (porosity versus horizontal permeability, Figure 10). Since undifferentiated sandstones are by far the most dominant sediment type, the other lithofacies will be compared with them. The main observations from the cross-plots are listed below:

- *Aeolian sandstones fully overlap with undifferentiated sandstones (Figure 11)*
  Only very few aeolian data points are present in the <12% porosity range. No clustering of aeolian data is observed in the >12% porosity range.
  A sensitivity check was done through an alternative quick-look facies interpretation based on the same vintage AppleCore facies listings. This so-called Clefacies scheme assigns an aeolian sandstone interpretation to all facies with a bimodal grain size distribution. This probably overestimates the proportion of aeolian sandstones, but does not change the observation of a large overlap with the undifferentiated sandstones (Figure 12).
- *Pebbly sandstones fully overlap with undifferentiated sandstones*
  Extraclast pebbly sandstones occur in the entire porosity range (Figure 13). Where present in the <16% porosity range, they appear to plot in the higher permeability ranges. Intraclast pebbly sandstones also cover the entire porosity range (Figure 14), but do not show a similar permeability trend.
- *Conglomerates plot in the lower porosity ranges, but in the higher permeability ranges*
  This trend cannot be observed in the cross-plots for Richfacies, because only very few plugs from the studied cores have been drilled in this lithofacies (Figure 10). More conglomerate data points can be seen when considering the entire Groningen plug database and applying the electrofacies scheme instead of Richfacies (Figure 15). There is a trend from more data points in the lower porosity ranges to less data in the higher ranges, with an approximate boundary at around 16%.
- *Mudstones plot in the lower porosity/permeability ranges, but still have significant overlap with the undifferentiated sandstones (Figure 16)*
  This is remarkable since mudstones would be expected to plot in the lower porosity and permeability ranges only. There are several possible explanations for this (overestimation of clay content, heterogeneity, sampling bias), but this was not further investigated. The overall impact on the property modelling approach is expected to be limited.

The cross-plots described above suggest that it is not feasible to pursue a facies-based approach for improving property models in Groningen, at least in any more detail than the three-fold electrofacies subdivision. It is realized that the cross-plots could potentially mask any lateral or proximal-to-distal depositional trends, or differences between Upper and Lower Slochteren sequences. This is further investigated in section 5.6 of this document.

A potential source of error could be that the facies allocated to a core plug is not exactly the same as was described for the corresponding core interval, e.g. because plugs represent a finer scale of sampling than the core descriptions. This concept was tested for a set of 500 plugs from the Uithuizermeeden-1A well. It was concluded that the effect of such errors is probably very small, though further testing on other wells could be considered.

4.2 Cross-plotting porosity/permeability data per grain size class

Some specific textural sediment properties potentially related to reservoir quality are grain size and sorting. Well-sorted sandstones have higher porosities than poorly sorted sandstones. Coarser sandstones tend to have larger pore throat diameters than finer sandstones, which results in higher permeabilities. No detailed information is available on the sorting of the cored intervals, but grain size has consistently been logged and has been extracted from AppleCore lithofacies listings of eight of the study wells. Figure 17 shows the locations of these wells, the applied (refined) Wentworth grain size scale, and a histogram of the relative abundance of each class. The wells represent the full proximal to distal range of the Groningen field. More than 80% of the sediment falls in the very fine upper to medium lower grain size range.

Figure 18 show a cross-plot of plug data from the eight cores, colored by grain size class. The overlap between the various classes is such that no clear trend is seen. Figures 19 to 24 show the same data with different grain size classes highlighted as red data points. These show that the overlap is obvious for the very fine and fine sandstones, i.e. for the bulk of the data points. For all coarser grain classes there may be a slight tendency to plot in the higher permeability ranges. However, the paucity of data points in these classes prohibits a closer assessment.

In summary, it is concluded that no obvious relation is seen between grain size and reservoir quality. The results of the eight study wells do not warrant a more extensive review incorporating all other cored wells.

4.3 Electrofacies proportion maps per reservoir zone

A series of maps have been prepared to review the areal distribution of electrofacies. The results are shown in Figures 25 to 29. For each reservoir zone, the proportion of conglomerate, sandstone and mudstone is given, together with a representative example facies map for one specific model layer in the subject zone. All the zones are largely dominated by the sandstone facies. The conglomerate facies is most widespread in unit LSS.1res (Figure 25), but also occurs towards the southern margin of the model area in other reservoir zones. The proportion of mudstone is highest in the northern part of unit USS.3res (Figure 29).

4.4 Cross-plotting porosity/permeability data per reservoir zone

Figures 30 to 34 show a series of core porosity-permeability cross plots for the reservoir zones only. The left-hand plots show plug data from all the cored wells, the right-hand plot only shows the data from cores revisited for the current study. Red-colored points highlight data from one specific reservoir zone as indicated in the legend.

A general observation is that the left- and right-hand cross-plots show very similar trends. This indicates that the selection of cores that has been investigated in the current study is representative for the entire core database.

Comparing results from individual reservoir zones leads to the following observations:

- The porosity classes >24% are best represented in units LSS.2res, USS.1res and USS.2res.
- There is a trend of increasing permeability values going from the deepest to the shallowest reservoir zone. The only exception to this is the basal LSS.1res zone which has data points scattered over the entire data cloud. The number of data points for this zone is limited compared to the other zones.

The trend of upward increasing permeability is difficult to explain with facies trends, because these have not been observed. There is vertical variability in the proportion, for example, of purely aeolian sandstone, but the facies-based cross-plots do not indicate a clear trend of higher permeabilities for this specific facies. Alternatively, there may be a depth-related trend. This may be an absolute true-vertical trend, in which case a structural control is probably the root cause. Or the trend is relative to, for example, the gas-water contact, in which case a diagenetic pore fluid control can be assumed. Depth-related trends in permeability are beyond the scope of the current study and are investigated in parallel studies.

5. Discussion of results

5.1 Feasibility of creating a facies model

The feasibility has been investigated of steering the interpolation of reservoir properties away from well locations with a sedimentological or lithofacies model. Such a facies model should be a refinement of the threefold electrofacies subdivision applied in GFR2012, but less detailed than the lithofacies model tested in GFR2003. The first objective was to split between purely aeolian dune sandstone and undifferentiated sandstone. This was done by detailed meticulous checking and reviewing of existing core descriptions from a subset of 20 cored wells in the Groningen area. A possible next step could be to further subdivide the 'undifferentiated sandstone' into meaningful smaller populations.

The result of the core study was that only a very limited percentage of the sandstone can be interpreted as purely aeolian dune deposits (Figure 9). The plug measurements of these aeolian sandstones are completely overlapping with the undifferentiated sandstones(Figure 11). These two observations indicate that there is no added value in modeling a separate aeolian dune lithofacies. Extending the aeolian facies population by including all bimodally sorted sandstones does not change the above observations.

The porosity ranges of the conglomerate, pebbly sandstone and mudstone lithofacies largely coincide with the undifferentiated sandstone lithofacies as well, but the relative proportion of lower-range porosities is higher. The areal distributions of these non-sandstone lithofacies are given by the proportion maps per reservoir zone (Figures 25 – 29). Hence, it is feasible in principle to create a threefold conglomerate-sandstone-mudstone facies model. Such a model should rather be based on electrofacies instead of lithofacies to circumvent a potential plug sampling bias; there is a tendency to avoid drilling plugs in mud-rich or conglomeratic core intervals because of the high chance of failure.

It was also tested if a facies model based on grain size only could bring a meaningful result (Figures 19 – 24). This is not the case; based on available plug data, there is no obvious relation between porosity and grain size.

5.2 Feasibility of applying facies models in the Groningen static modelling workflow

A meaningful subdivision of the Rotliegend reservoir sandstone facies could not be established in this study. It is feasible to build a simple facies model on the basis of electrofacies, possibly with supporting information from core measurements. But can such a model be applied to obtain a representative distribution of porosity over the extent of the model area? The following considerations may serve to answer that question:

- Non-sandstone lithofacies only comprise a very small part of the entire reservoir interval
- The porosity ranges of non-sandstone lithofacies show a large overlap with the sandstones
- Non-sandstone lithofacies mainly occur towards the southern and northern margins of the model area
- The larger central part of the Rotliegend reservoir consists of various sandstone lithofacies, but without distinctive suits of reservoir properties.

It is concluded that a facies-based approach is not very suitable for modelling porosity in the Groningen field. Better results can probably be obtained with an alternative method based on a seismic inversion dataset. This dataset has a much lower vertical resolution, but provides measured quantitative information on the porosity distribution away from well locations. This is because of the physical relationship between porosity and seismic response. It is worthwhile to note that lower porosity areas expected from the facies proportion maps, i.e. conglomeratic in the south and clay-rich in the north, are also represented in the seismic inversion data set. This serves to illustrate that also an inversion-based model should still be guided by geological understanding – which this study, and those before it, provide.

5.3 Homogenous porosity distribution in the sandstone lithofacies

Porosity distributions of the various lithofacies types are seen to be largely overlapping. This is in itself a remarkable observation, because one would intuitively expect to see differences between for example damp sandflat, fluvial or aeolian dune deposits. This section aims to provide a tentative explanation for this, based on the following basic observations:

- A narrow overall grain size distribution dominated by fine sand
- Paucity of dune slipface deposits, i.e. low- to high-angle cross-bedded sandstones
- Abundance of aeolian sandflat deposits
- Very flat depositional surface, no lateral thickness variations, no erosional scouring
- Northern extent of thin conglomeratic layers
- Rapid lateral and vertical lithofacies variations
- Many intervals show evidence for both fluvial and aeolian processes

The field-wide depositional setting with pebbly or conglomeratic lithofacies in the south and more clay-rich lithofacies in the north clearly represents a large-scale proximal-to-distal trend. This trend can be traced further to the south where conglomerates become more abundant (Ref. 13), and further to the north where sandstone intervals become increasingly thinner or pinch out completely.

The Groningen field area is envisaged as a low-relief depositional plain connecting these two extremes. Sand must have been introduced to the plain either by fluvial streams coming from a source area in the south, or by winds with a strong east-to-west component. The sedimentary characteristics point to a variety of depositional processes including transport by fluvial streams, suspension settling in ponded areas, desiccation and subsequent transport as clay clasts, wind ripple and dune sedimentation, adhesion of wind-blown sand onto damp surfaces, and repeated precipitation and dissolution of evaporate minerals.

No separate fluvial fairways or aeolian dune fields could be mapped in the Groningen field area. Within each reservoir zone there is a broad pattern of east-west trending facies belts (Ref. 2). From south to north, these belts grade from pebbly fluvial to sandy fluvial to mixed fluvial-aeolian to aeolian sand flat to lake margin. But the transitions from one belt into the other are ill-defined and highly gradual. No clear indications have been found for basal fluvial erosion. This suggests that periods of high fluvial run-off did not lead to scouring of channel systems, but rather to a sheetflood-like extent over a flat area. The almost complete absence of cross-bedded aeolian sands indicates that migrating dunes in the Groningen area had a very low preservation potential. Factors controlling the preservation of dunes include a gradual subsidence of the depositional surface accompanied by a sufficiently large supply of sand. This results in lowering of part of the dune below the groundwater table, hence in protection from erosion during subsequent storms. Such conditions apparently did not prevail. The importance of wind transport is evidenced by the abundance of dry to damp sandflat deposits, but only toe sets of dunes have been preserved at best. Any depositional relief that is created by migrating dunes during dry periods is bound to be levelled out rapidly. The result is a flat depositional plain where wind and running water continuously redistribute the available sediment. Individual beds preserved in the rock record will carry the characteristics of the last depositional process before burial, but may also have inherited characteristics from earlier processes. The heterolithic zones separating the sand-dominated reservoir zones represent periods of depositional quiescence when thin intervals with more fine-grained and low-energy deposits could accumulate. Larger-scale climatic variations, i.e. alternating periods of dryer and wetter conditions, are represented in the rock record by alternating intervals of dryer and wetter lithofacies.

The above observations and interpretations from the Groningen field are compatible with the larger scale depositional context of the Rotliegend. The Southern Permian Basin is thought to have been a highly underfilled and very slowly subsiding sedimentary basin. Sediment supply was very low compared to the available accommodation space and depositional processes were redistributing rather than depositing the available sediment. The Groningen area must have been a relative high that was subjected to frequent erosion. The Lauwerszee Trough area west of the Groningen field was lower-lying and has acted as a catchment area by virtue of the prevailing easterly winds. This suggests that local physiographic conditions have exerted a primary control on the distribution of lithofacies throughtout the extent of the Southern Permian Basin.

The consequences for the Groningen field in terms of reservoir properties can now be understood. Repeated erosion and redeposition of sediment lead to a high degree of sorting. Lithofacies may differ in terms of sedimentary structures, but not so much in dominant grain size and sorting. In cases where small amounts of finer- and coarser-grained sediment are intermixed, this only has a limited effect on reservoir quality.

6. Conclusions and recommendations

- Facies modelling cannot help to refine the 3D porosity distribution in the Groningen field. Nevertheless, geological understanding used in this study and that of others, should always be used when trying to refine the porosity distribution with other methodologies (e.g. seismic inversion)
- Porosity-permeability relationships do not depend on lithofacies type or grain size distribution
- The porosity-permeability relationship seems to show depth dependency. It should be investigated if this is associated with absolute TVD depth, depth relative to the gas-water contact, or otherwise. This could point to potential diagenetic effects. Many studies have shown that the reservoir quality of Rotliegend sediments is affected by post-depositional cementation and dissolution processes. For the Groningen field, no comprehensive assessment of the petrography and diagenesis of the Groningen field has been carried out to date.

References:

Ref. 1 NAM UIE/T/DPE, 2010: Bodemdaling door Gaswinning (EP201006302236)

Ref. 2 Visser et al., 2012: Groningen Field Review 2012 – Static Modeling and Hydrocarbon Volume Determination (EP201203204663)

Ref. 3 Oomkens, 1964: A Facies Interpretation of the Lower Permian (Rotliegend) Deposits of the northern Netherlands (Research Report R1153)

Ref. 4 Glennie, 1964: Desert Sediments – Lybia (KSEPL D 954)

Ref. 5 Nicholls et al., 1987: Sedimentological Description and Facies Definition of Cores from the Rotliegend Group, Groningen/Annerveen Area, North-Eastern Netherlands (RKTR 87.009)

Ref. 6 Cohen, 1991: Reservoir Geological Study of the Ten Boer in the Groningen Area with Special Emphasis on the Eemsmonding Area (NAM Report No. 19.403)

Ref. 7 Reijers and Kosters, 1993: Sedimentology of the Rotliegend of the Dutch Northern Onshore and Adjacent Offshore (NAM Report No. 23.124)

Ref. 8 Reijers et al., 1993: Lithofacies and their Interpretation: a guide to standardized description of sedimentary deposits (Meded. Rijks Geol. Dienst, 49)

Ref. 9 Ladipo, 1995: Upper Rotliegend Depositional Cycles: a Sequence Stratigraphic Approach and Regional Correlation, NE. Netherlands (NAM Report No. 28.238)

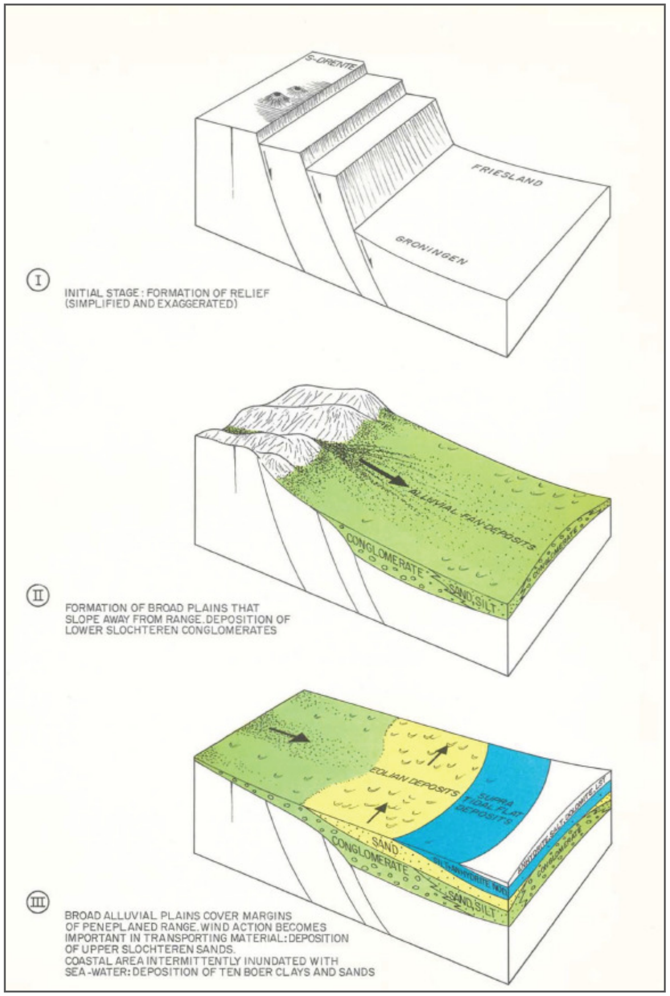
Ref. 10 ENRES International, 2001: Detailed Correlations at Regional and Local Scale of the Permian Rotliegend of NW Europe (Report EP01-280)

Ref. 11 Besems et al., 2002: Rotliegend Stratigraphy Groningen Field (EP200211002181)

Ref. 12 Pipping and Kraft, 2003: Groningen Field Static Modelling and Ultimate Recovery Determination, Volume 3, Reservoir Geological Modelling and Static GIIP Estimates (NAM200308000867)

Ref. 13 de Keijzer, 2015: Rotliegend Proximal Periphery Paleo-relief Assessment, NE Netherlands (EP201504200106)

Figures



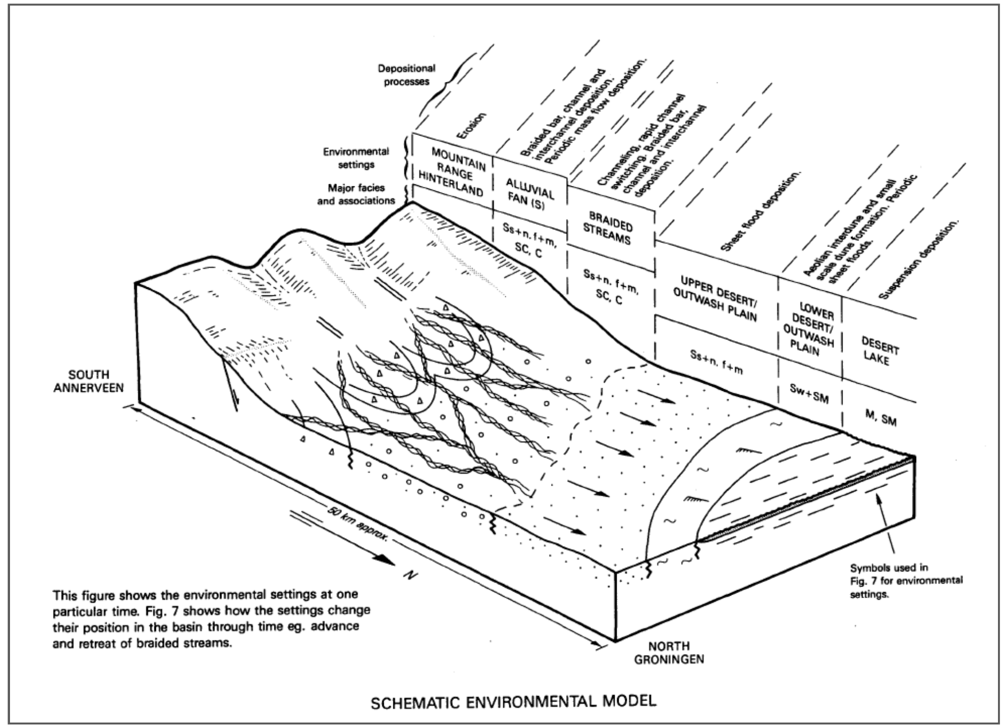


Fig. 2: Depositional environment for the Rotliegend in Groningen, after Nicholls et al. (Ref. 4)

Fig. 1: Sequence of deposition in the Rotliegend of the N. Netherlands", Oomkens, 1964 (Ref. 2)

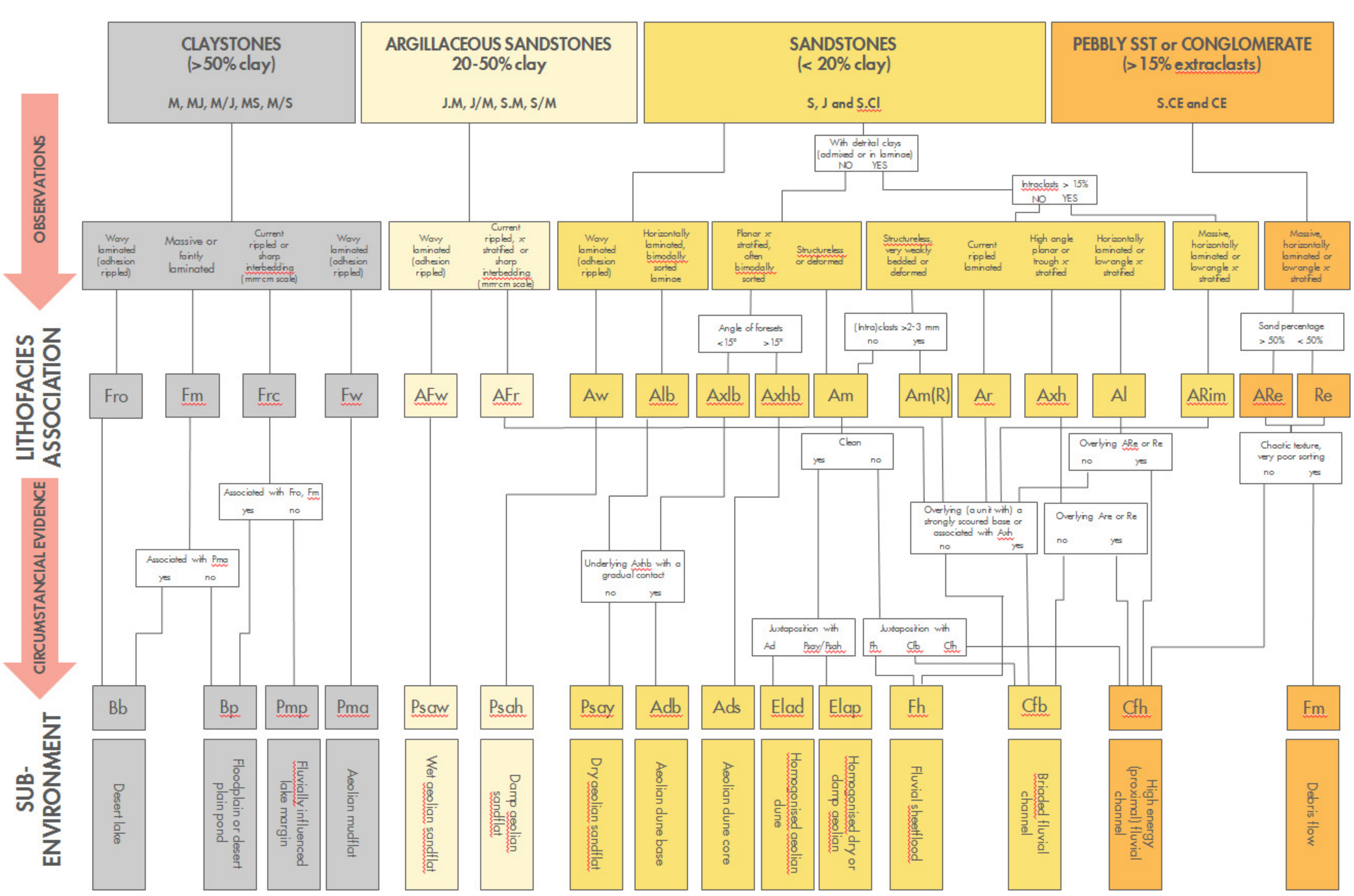


Fig. 3: Standardized lithofacies description and interpretation scheme for the Rotliegend

well name	interval top	interval base	thickness	lithofacies	lithofacies association	depositional subenvironment	formation
MWD- 1	2812.05	2812.1	0.05	M,mf	Fm	Cfb	ROSL
MWD- 1	2812.1	2812.17	0.07	S2l,l	Al	Cfb	ROSL
MWD- 1	2812.17	2812.33	0.16	S2l,xh	Axh	Cfb	ROSL
MWD- 1	2812.33	2812.53	0.2	S2l,xh	Axh	Cfb	ROSL
MWD- 1	2812.53	2812.59	0.06	M.S,l	Fm	Fh	ROSL
MWD- 1	2812.59	2812.66	0.07	S1u,xh	Axh	Fh	ROSL
MWD- 1	2812.66	2812.73	0.07	S1u,xh	Axh	Fh	ROSL
MWD- 1	2812.73	2812.74	0.01	S1u,xh	Axh	Fh	ROSL
MWD- 1	2812.74	2812.78	0.04	M,mf	Fm	Fh	ROSL
MWD- 1	2812.78	2812.84	0.06	S1u,xh	Axh	Fh	ROSL
MWD- 1	2812.84	2812.85	0.01	S1u,mf	Axh	Fh	ROSL
MWD- 1	2812.85	2812.93	0.08	S1u,mf	Am(R)	Fh	ROSL
MWD- 1	2812.93	2813	0.07	S1u,mf	Am	Fh	ROSL

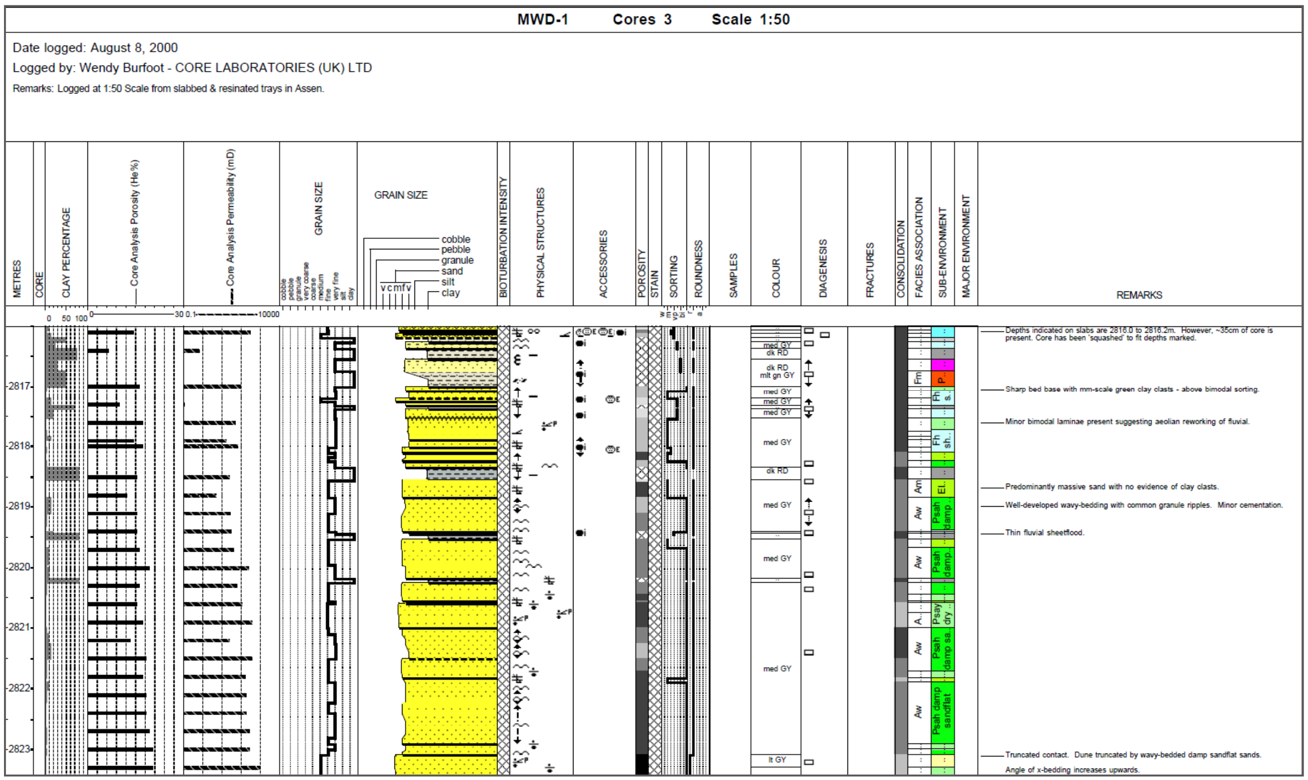


Fig. 4: Example of spreadsheet and graphical output from AppleCore core description software

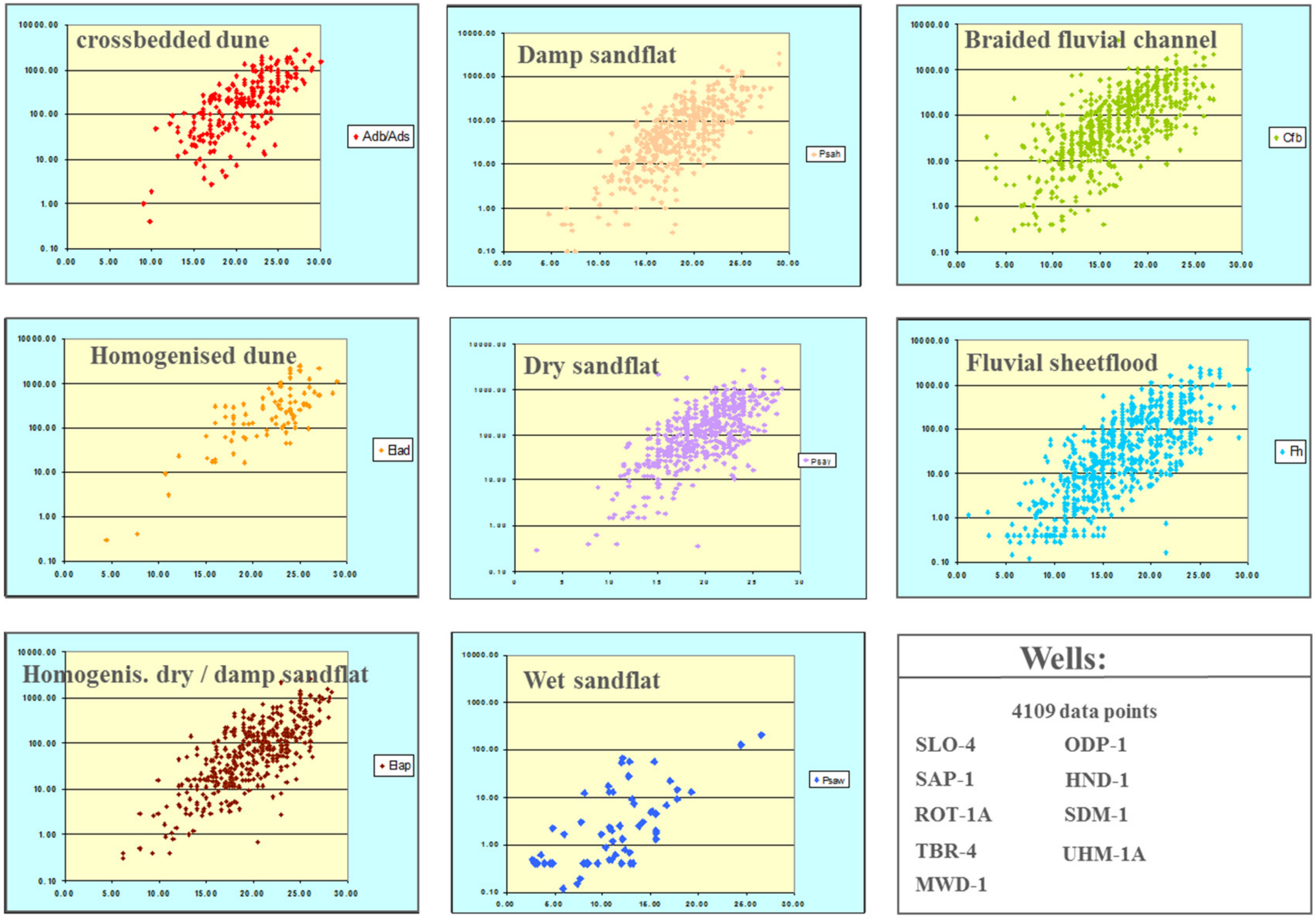


Fig. 5: Groningen Field Review 2003 (Ref. 11): Core porosity versus permeability cross-plots per lithofacies

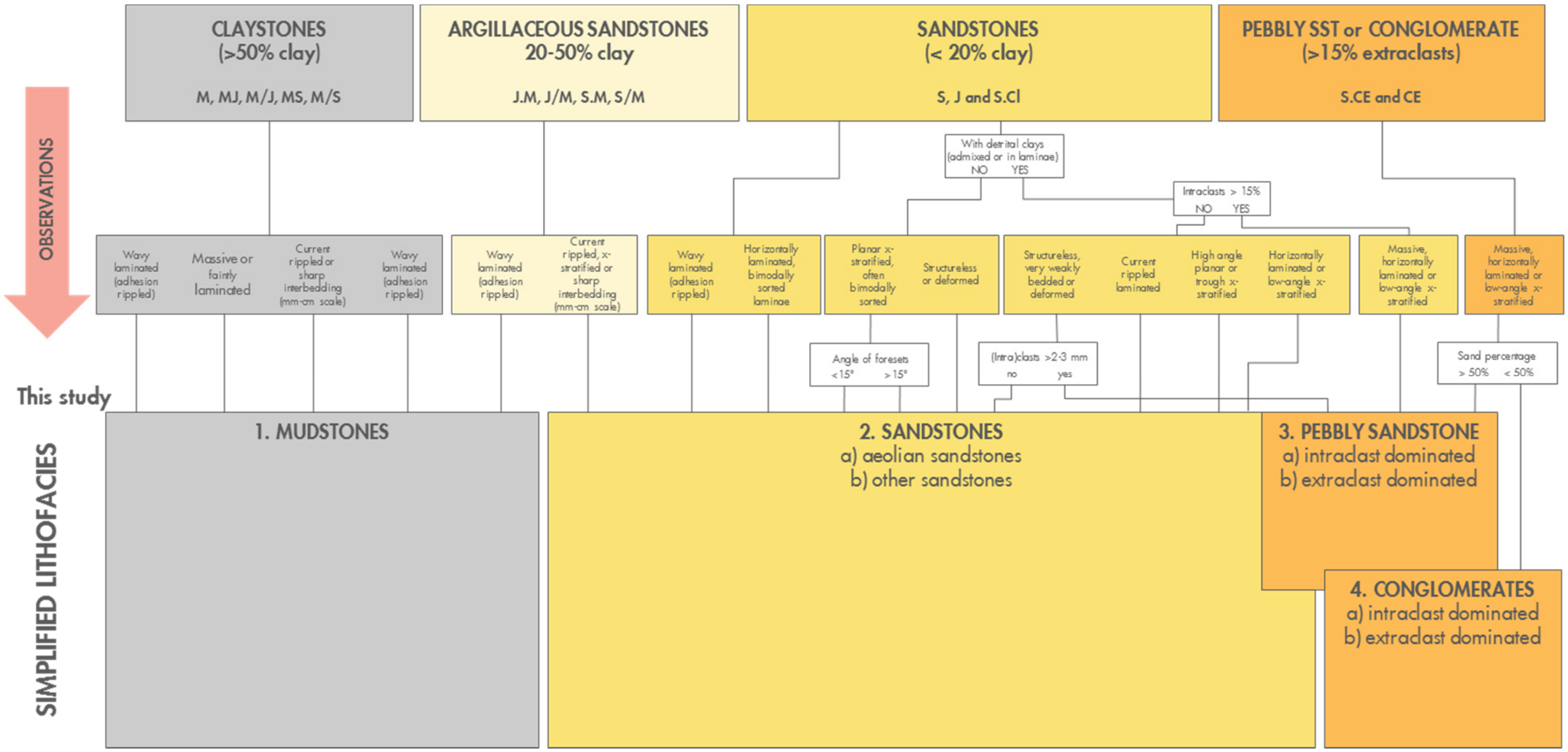


Fig. 6: Simplified lithofacies scheme for the description of Rotliegend core

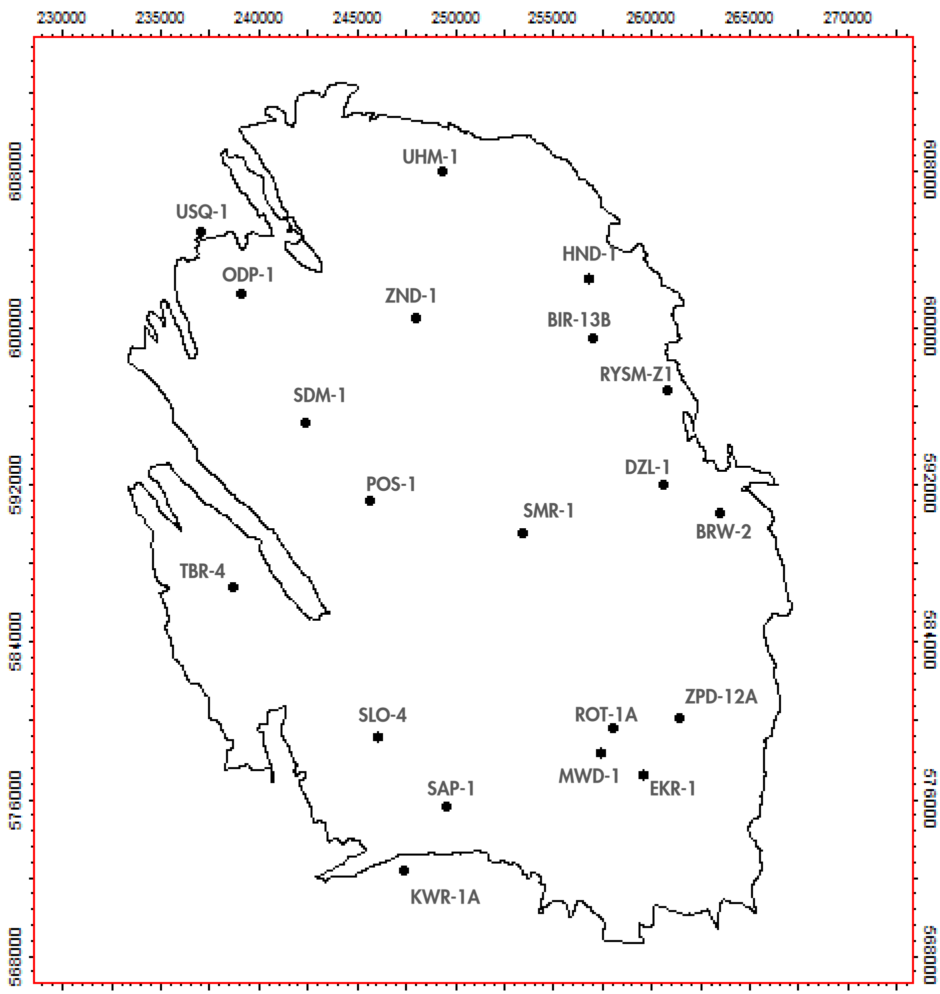


Fig. 7: Location map of cored wells used in this study

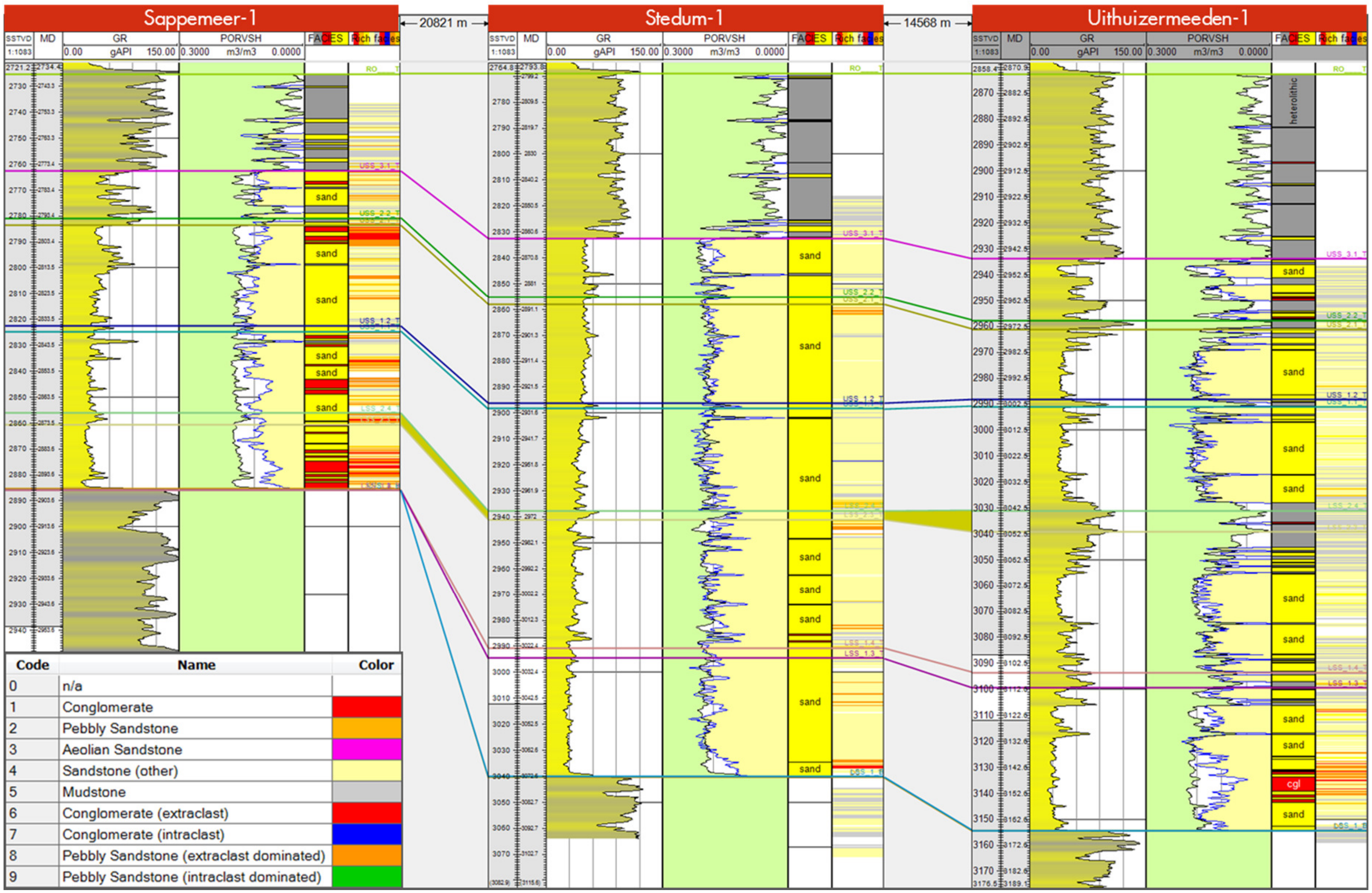


Fig. 8: Core descriptions of three wells. The “Rich facies” column is a lithofacies description based on the simplified lithofacies scheme (see inset legend). Left of this column is an electrofacies column based on the three-fold mustone-sandstone-conglomerate subdivision.

Lithofacies distribution of studied cores

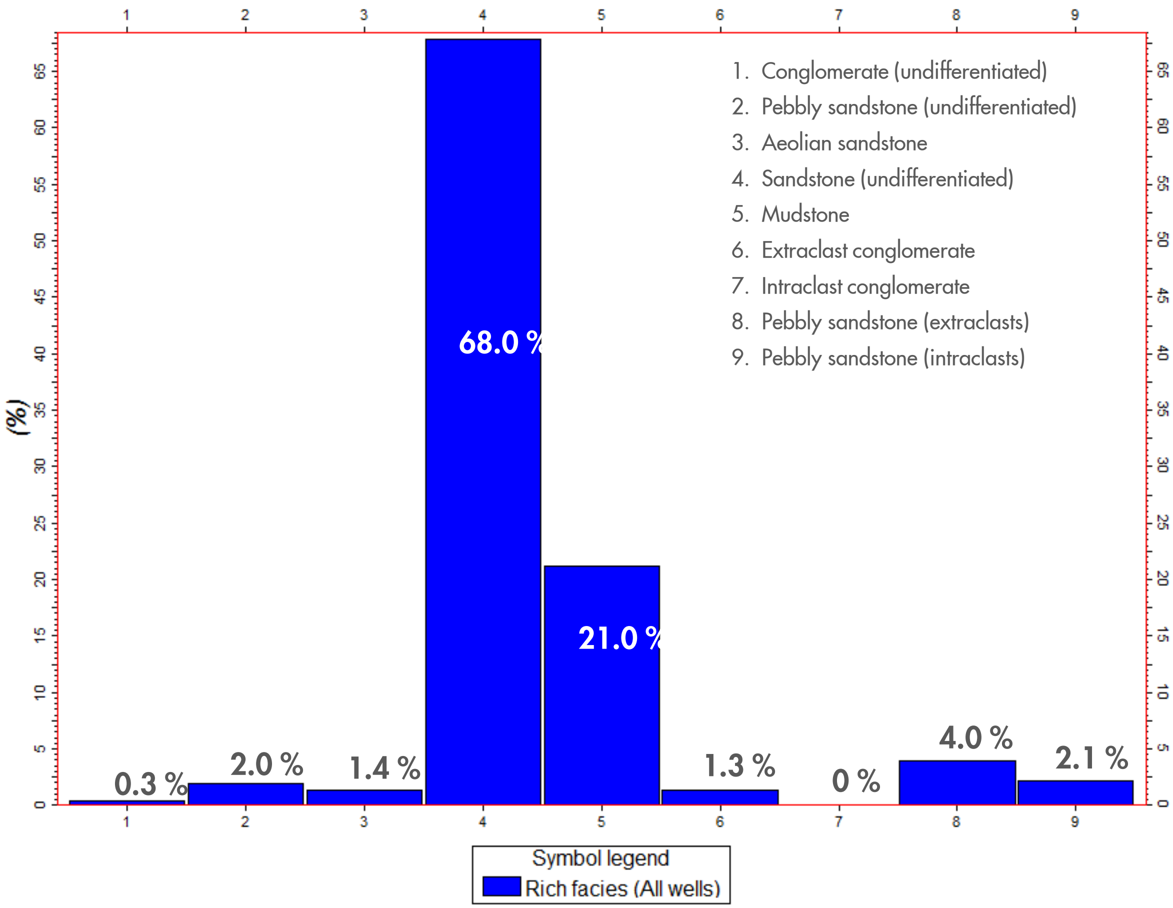


Fig. 9: Location map of cored wells used in this study

Plug data from 18 studied cores, colored by Richfacies

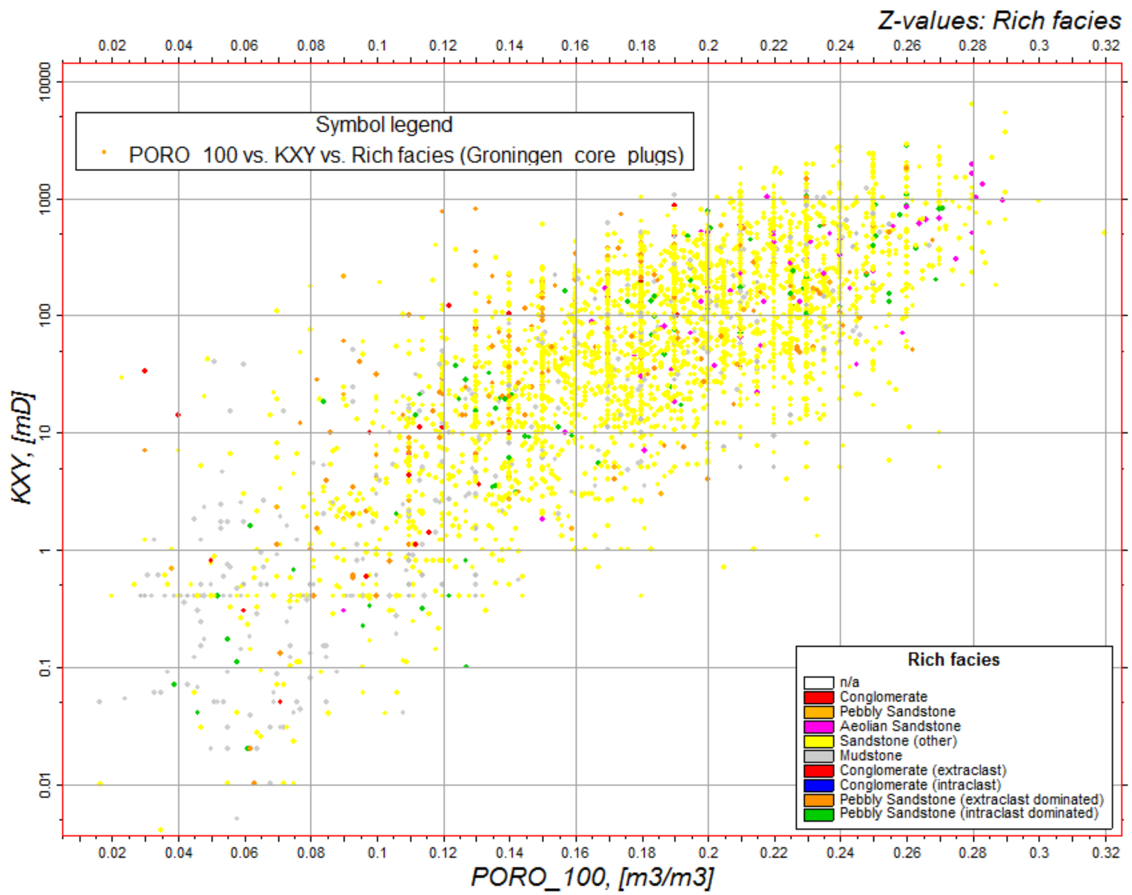


Fig. 10: Porosity-permeability cross-plot showing core plug data from 18 studied wells, grouped per lithofacies

Richfacies, aeolian and undifferentiated sandstones

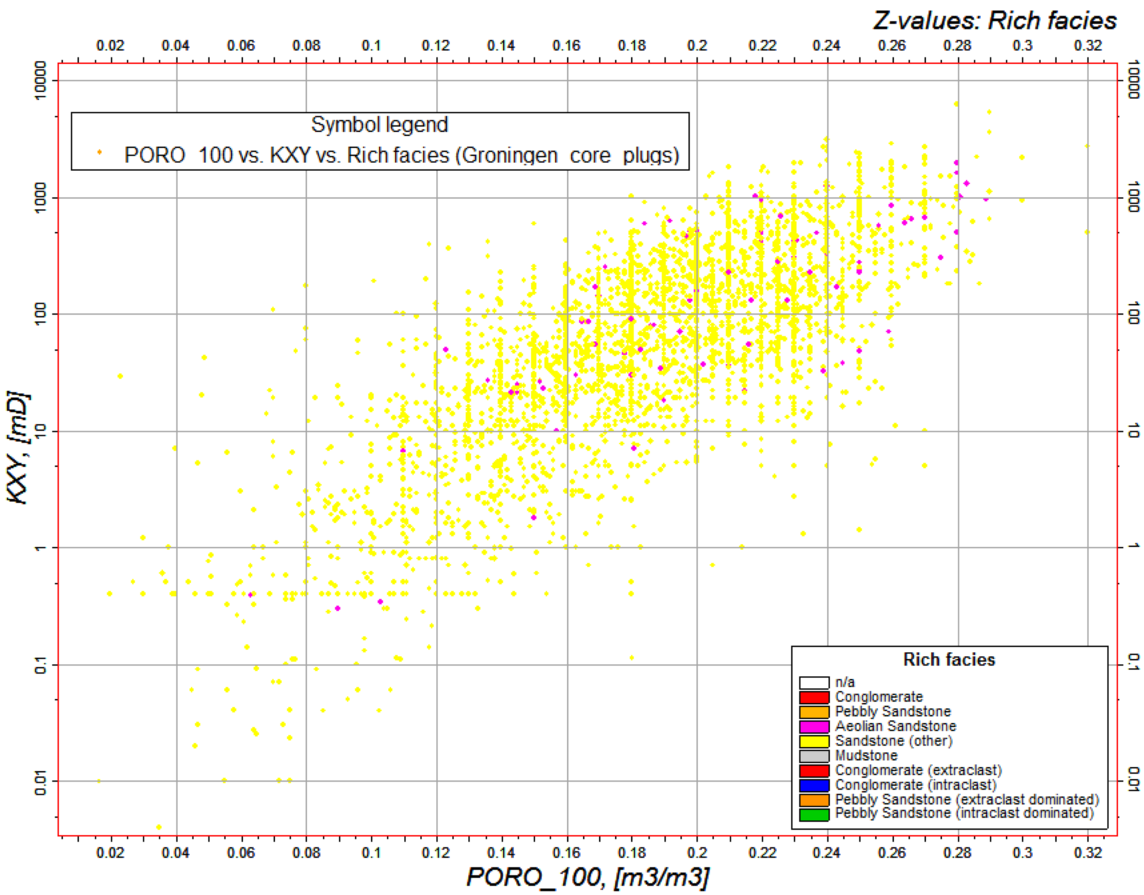


Fig. 11: Porosity-permeability cross-plot showing aeolian (purple) and undifferentiated (yellow) sandstone core plug data

Comparing Richfacies and Clefacies aeolian sandstones

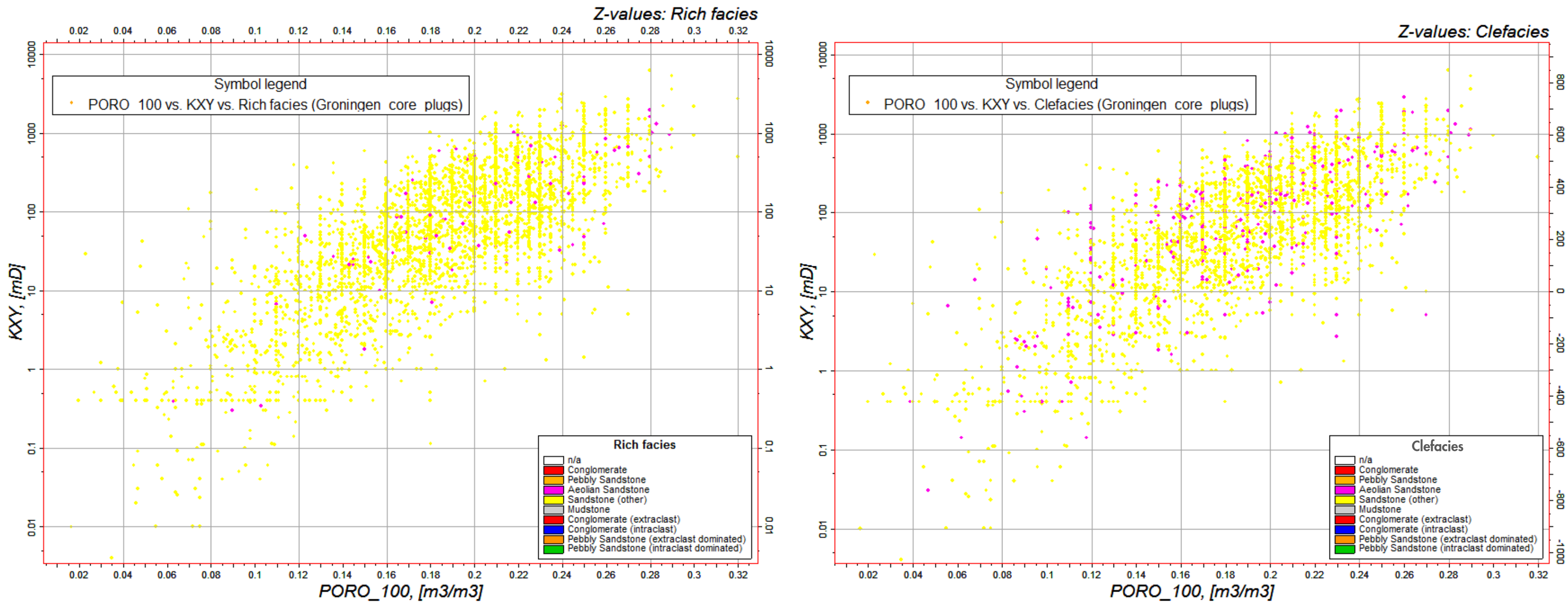


Fig. 12: Same as Fig.10 but comparing Rich facies (left) with Clefacies) data, see text for more details.

Richfacies, undiff. sandstones and extraclast facies

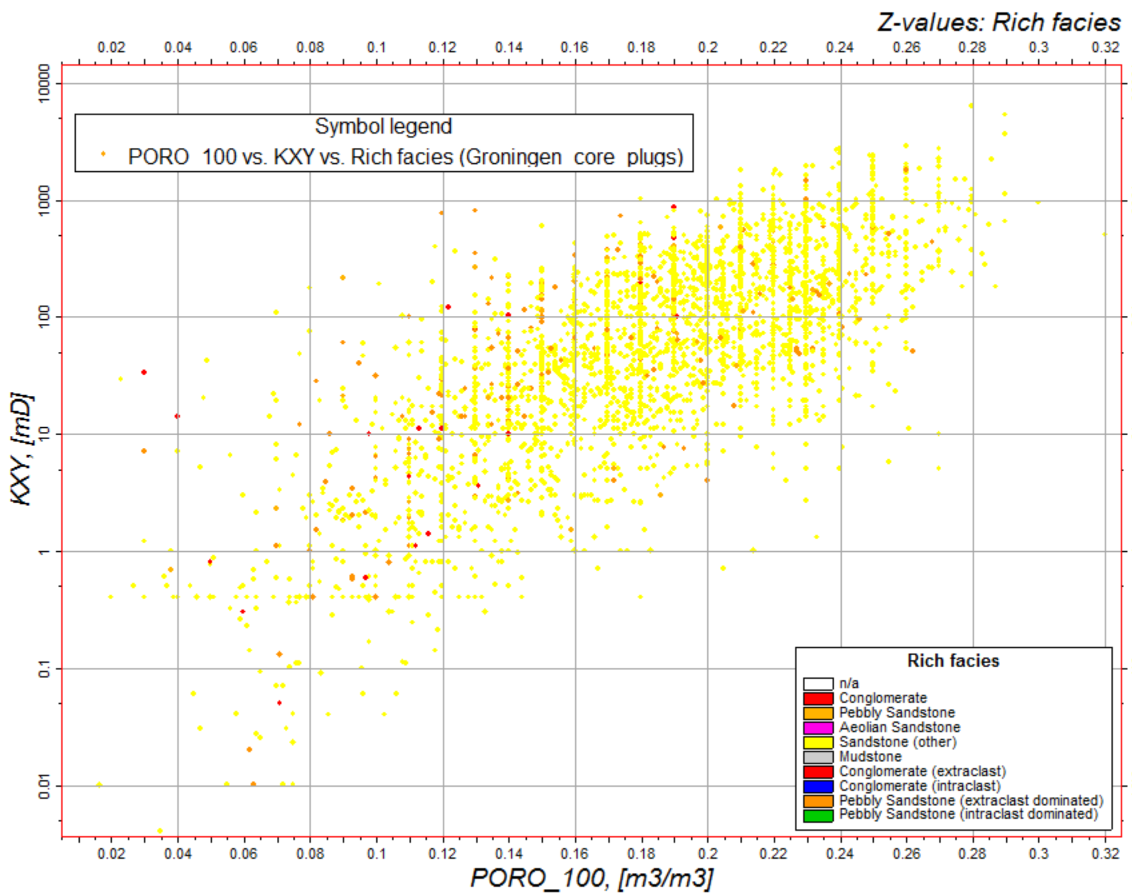


Fig. 13: Porosity-permeability cross-plot showing undifferentiated (yellow) and pebbly extraclast (shades of orange) sandstone core plug data

Richfacies, undiff. sandstones and intraclast facies

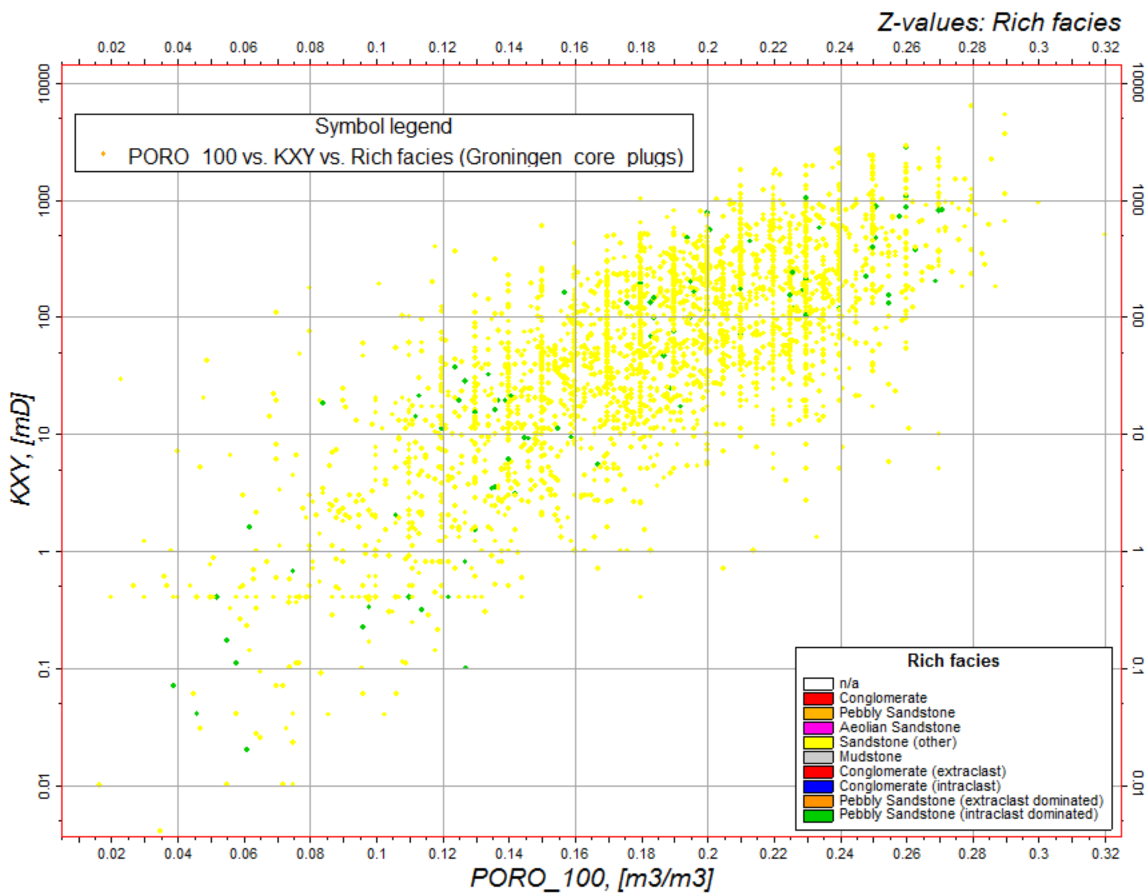


Fig. 14: Porosity-permeability cross-plot showing undifferentiated (yellow) and pebbly intraclast (green) sandstone core plug data

Full core database, conglomerates from electrofacies

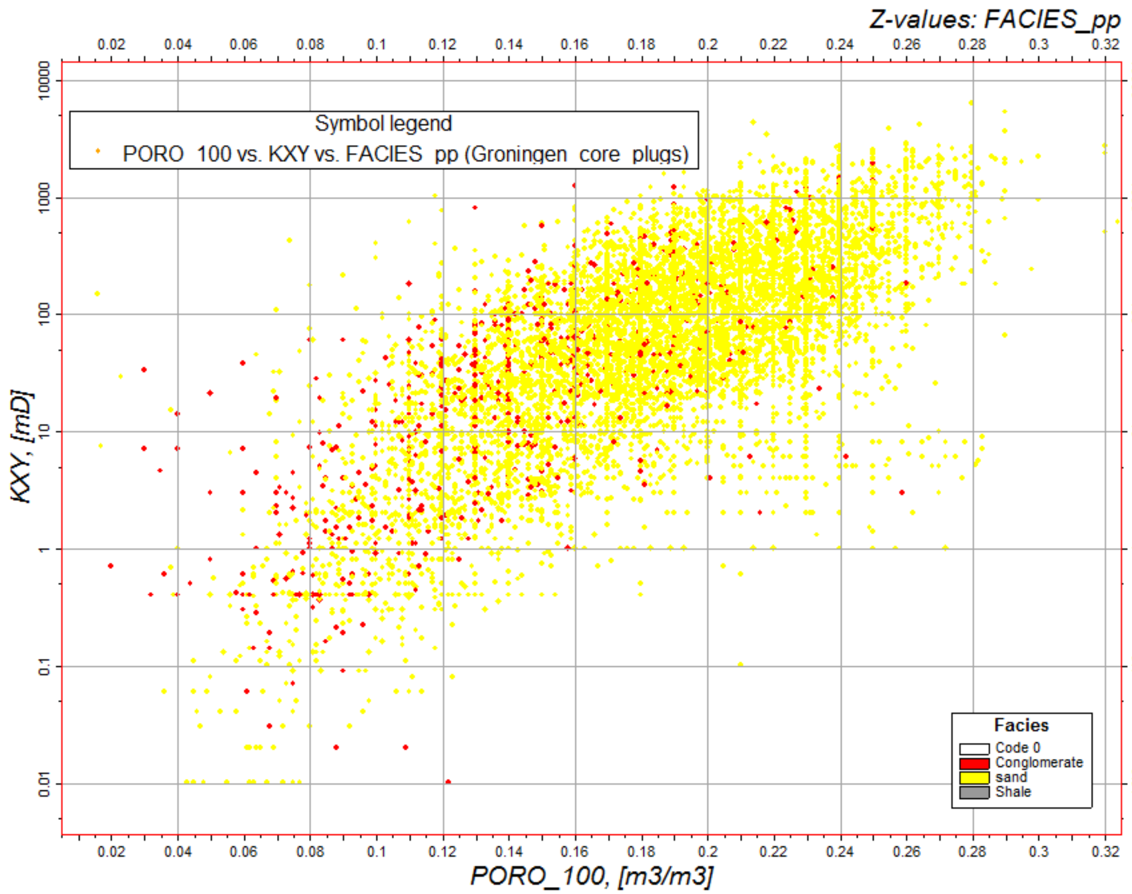


Fig. 15: Porosity-permeability cross-plot showing undifferentiated (yellow) and pebbly intraclast (green) sandstone core plug data

Richfacies, mudstones and undifferentiated sandstones

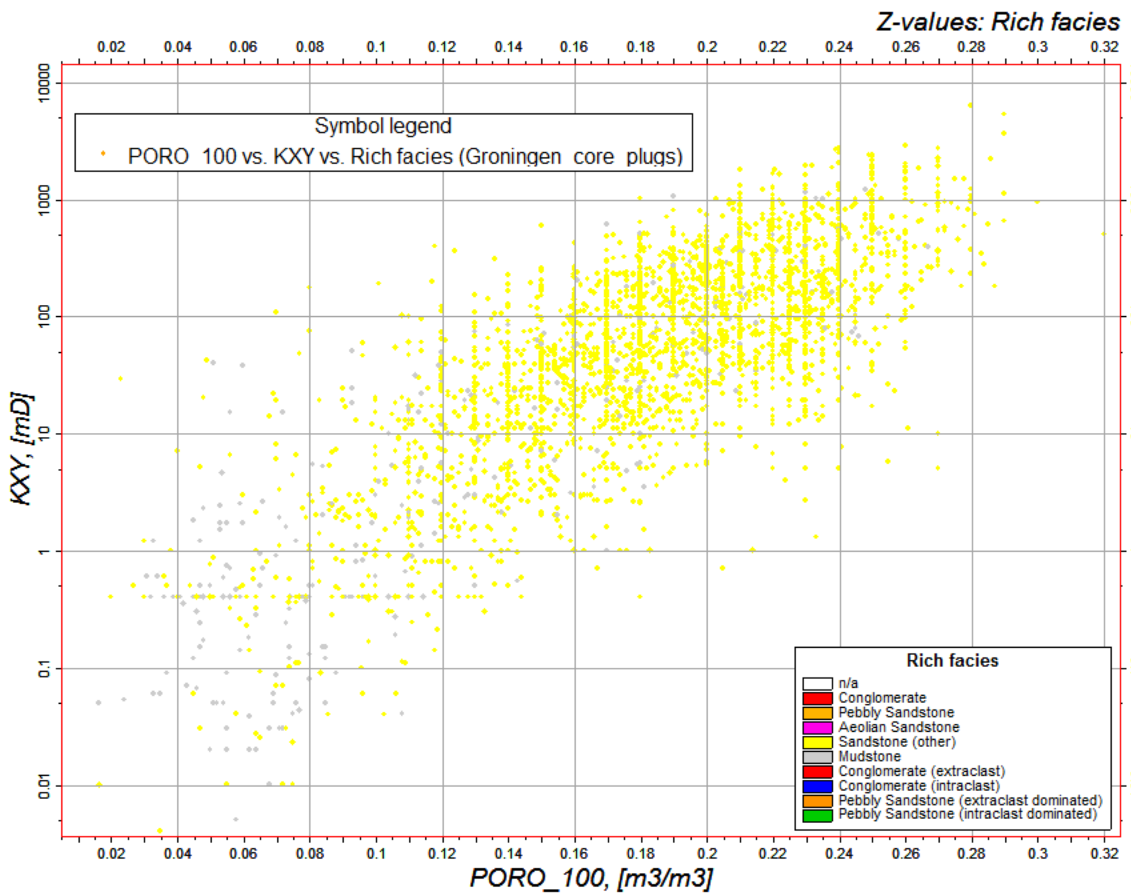
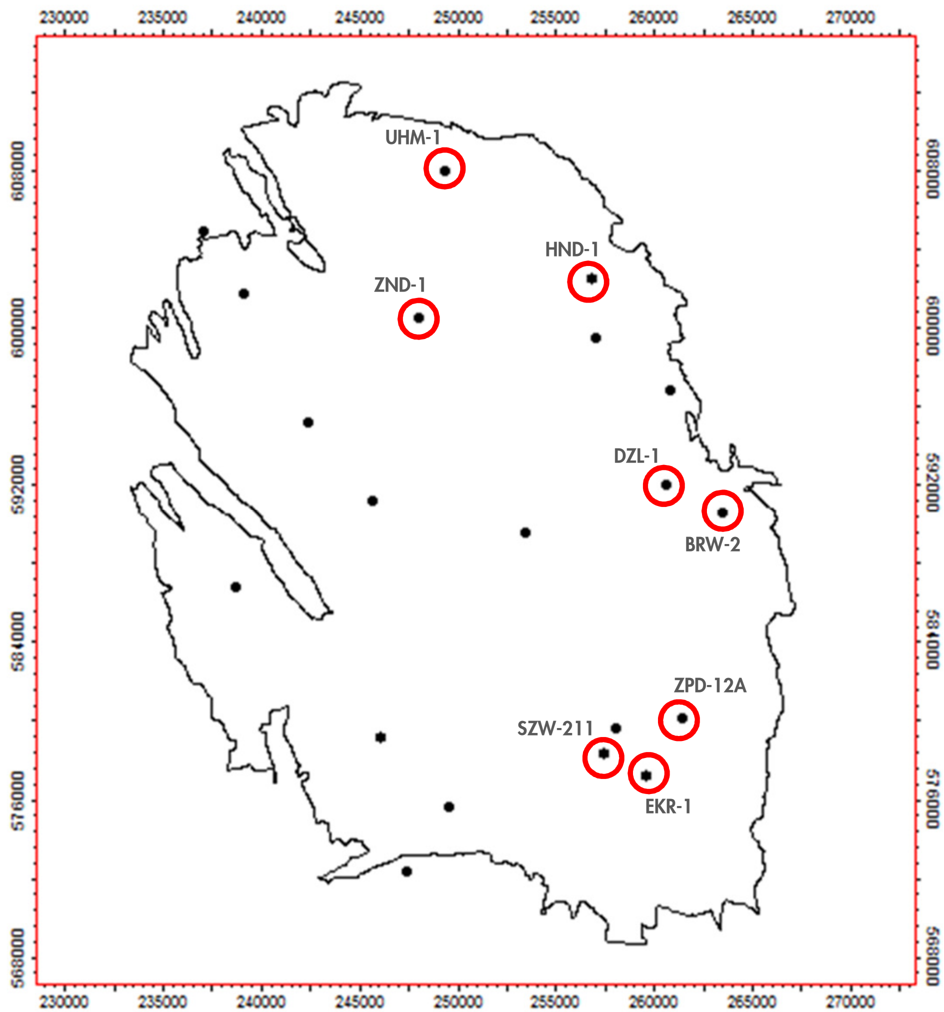


Fig. 16: Porosity-permeability cross-plot showing undifferentiated sandstone (yellow) and mudstone (grey) core plug data

Cores with detailed grain size information*



Wentworth grain size classes

1. Mud
2. Silt
3. Very fine lower
4. Very fine upper
5. Fine lower
6. Fine Upper
7. Medium lower
8. Medium upper
9. Coarse lower
10. Coarse upper
11. Very coarse lower
12. Very coarse upper
13. Gravel, pebbles

Proportion of grain size classes

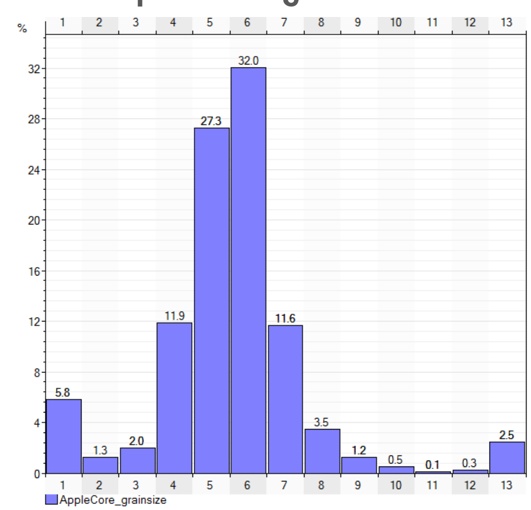


Fig. 17: Location of 8 cores with detailed grain size information, the histogram shows the total distribution for these wells

All grain size classes*

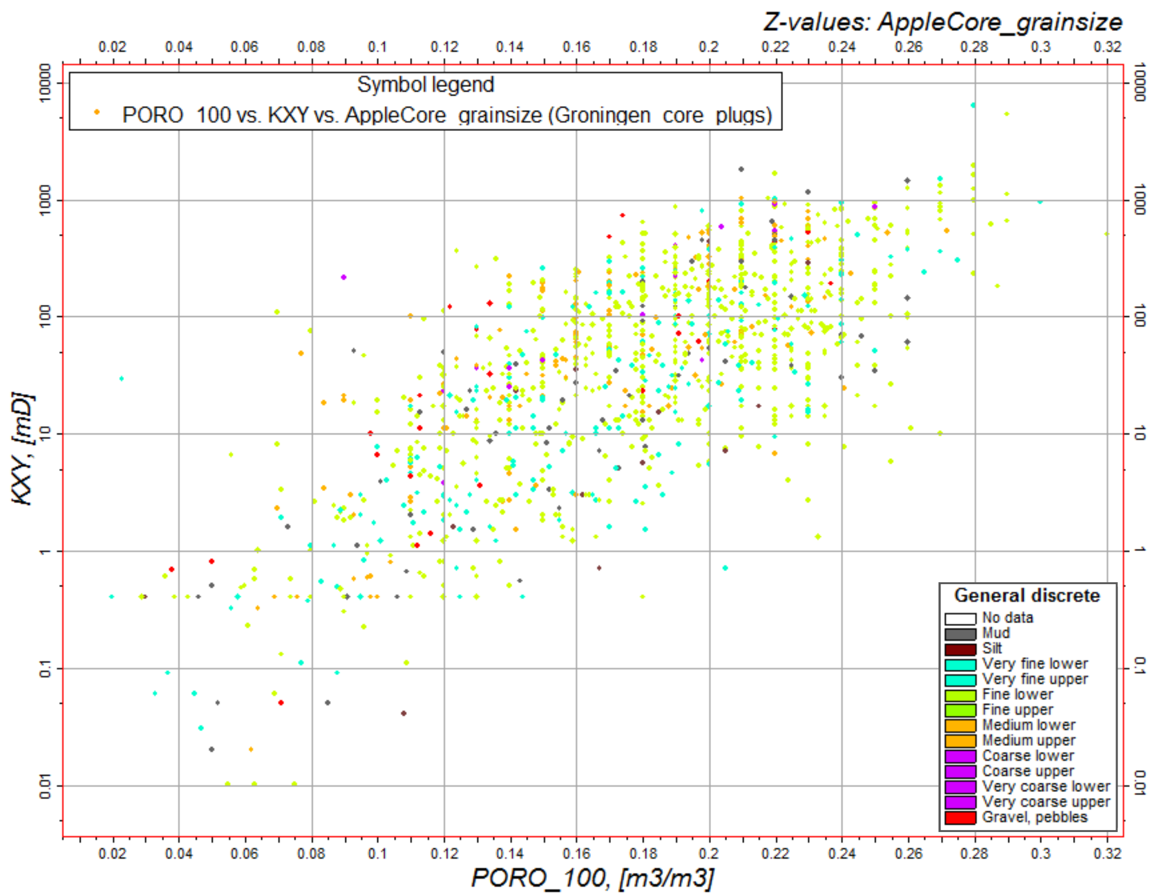


Fig. 18: Porosity-permeability cross-plot from core plug data, grouped by grain size class

All grain size classes*

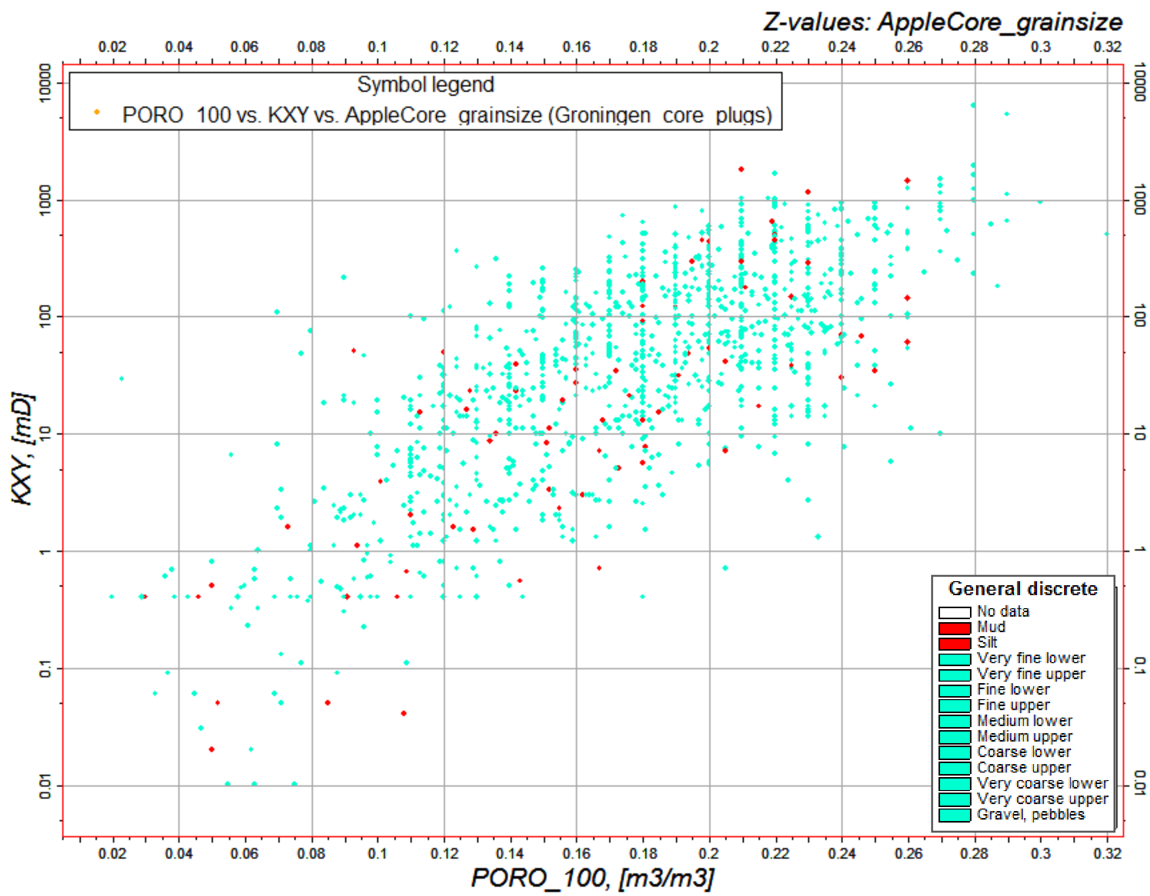


Fig. 19: Porosity-permeability cross-plot from core plug data, mud and silt plugs coloured red

All grain size classes*

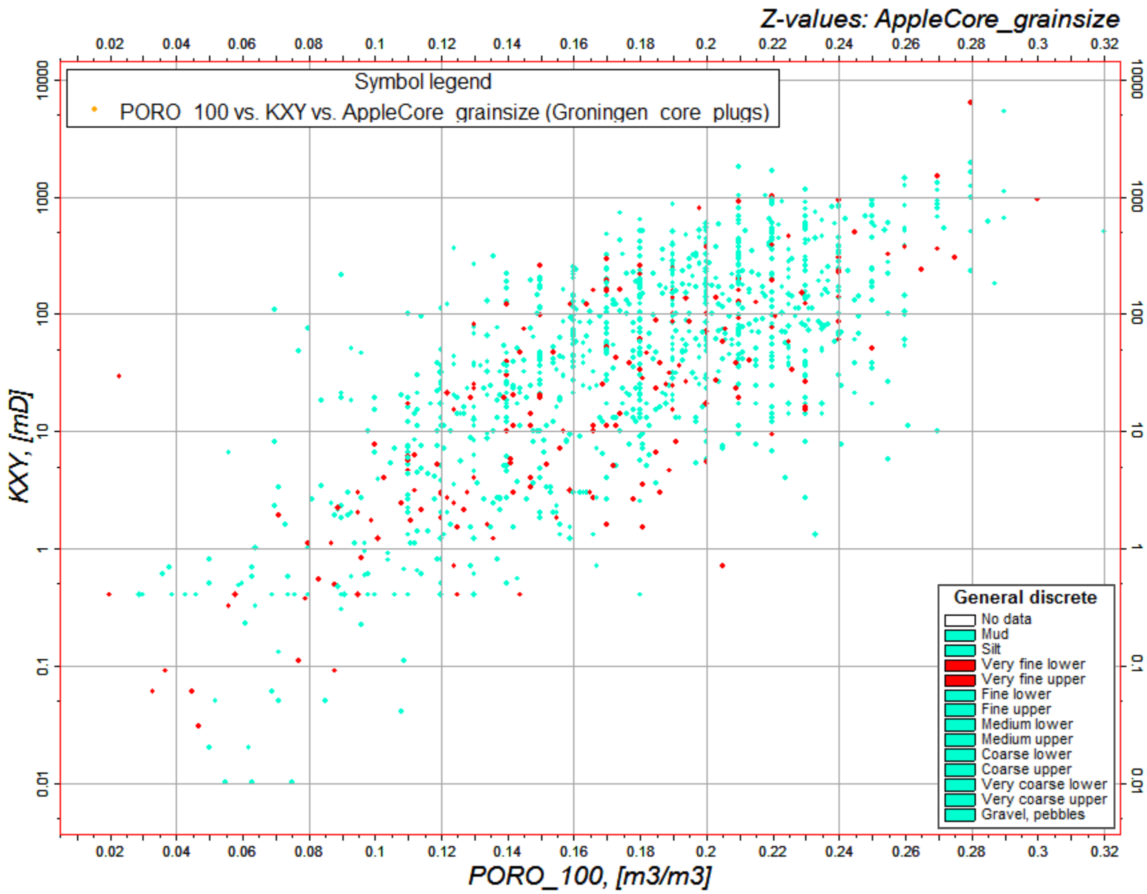


Fig. 20: Porosity-permeability cross-plot from core plug data, very fine sandstone plugs coloured red

All grain size classes*

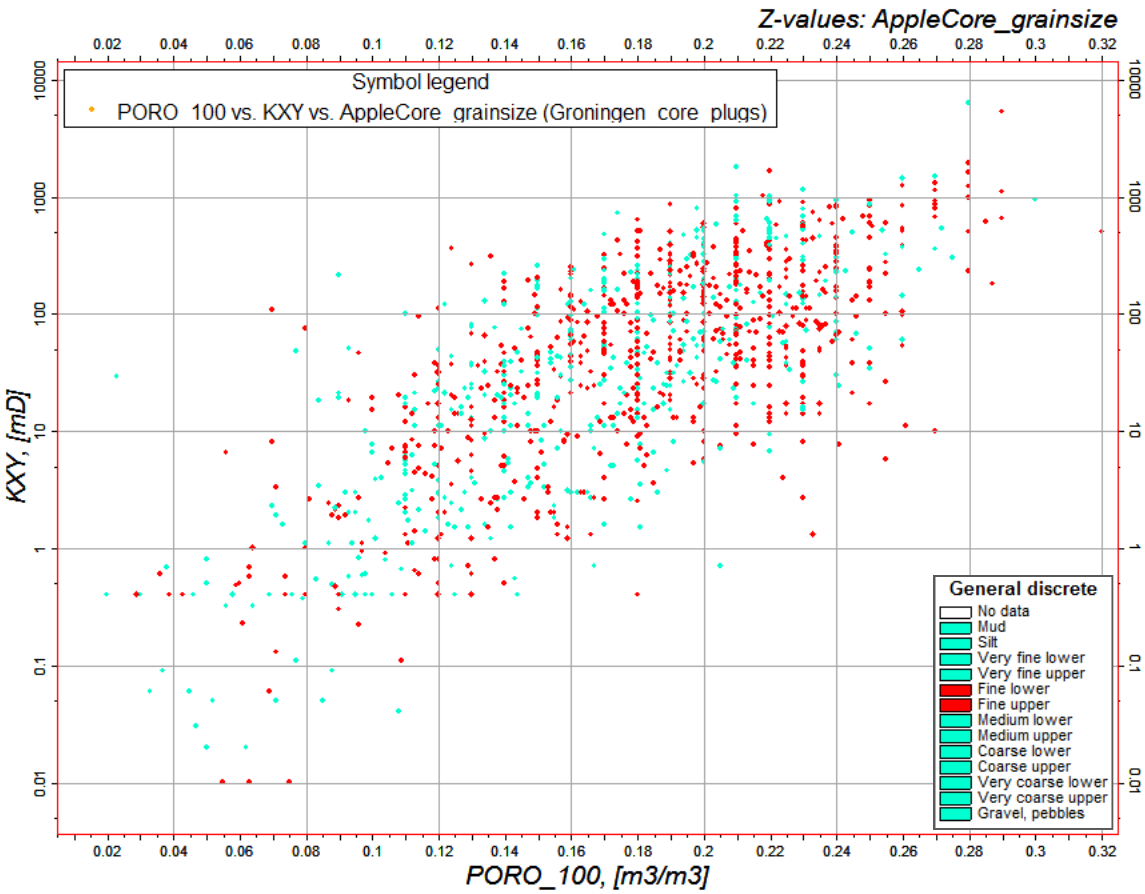


Fig. 21: Porosity-permeability cross-plot from core plug data, fine sandstone plugs coloured red

All grain size classes*

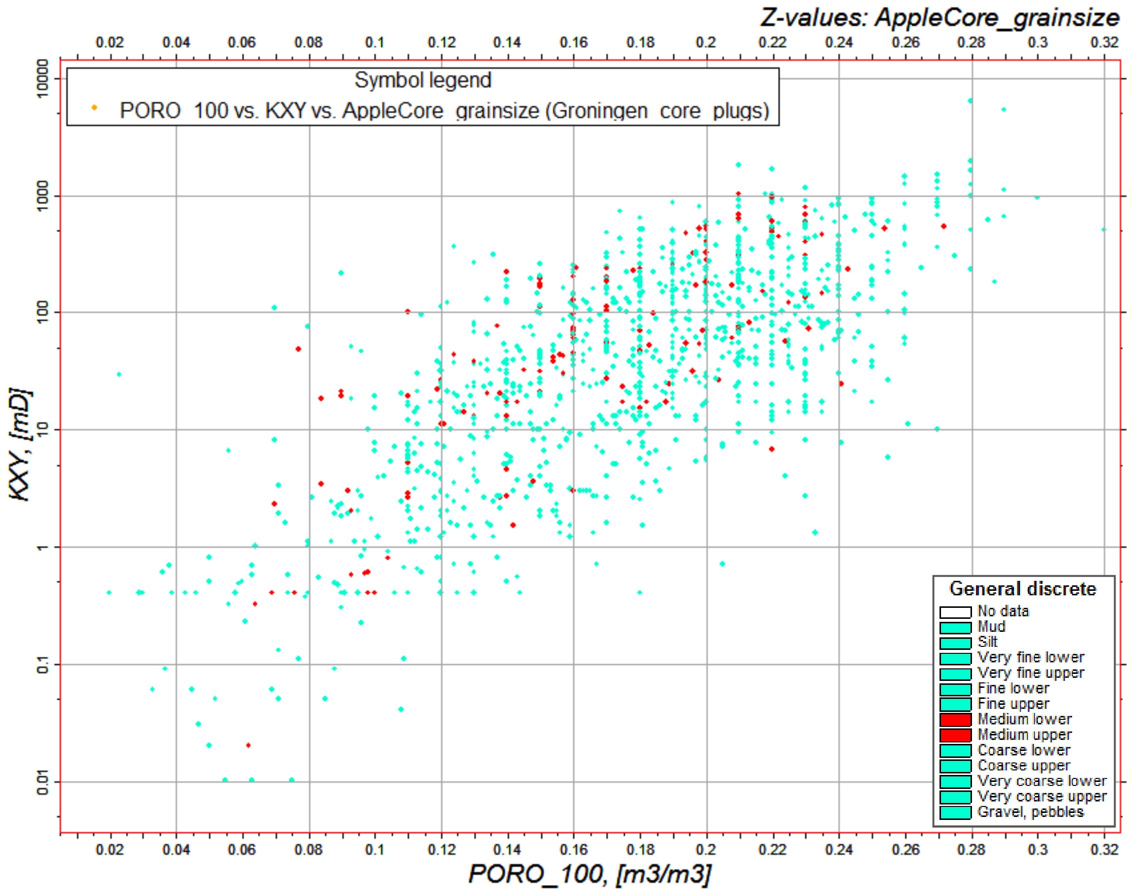


Fig. 22: Porosity-permeability cross-plot from core plug data, medium sandstone plugs coloured red

All grain size classes*

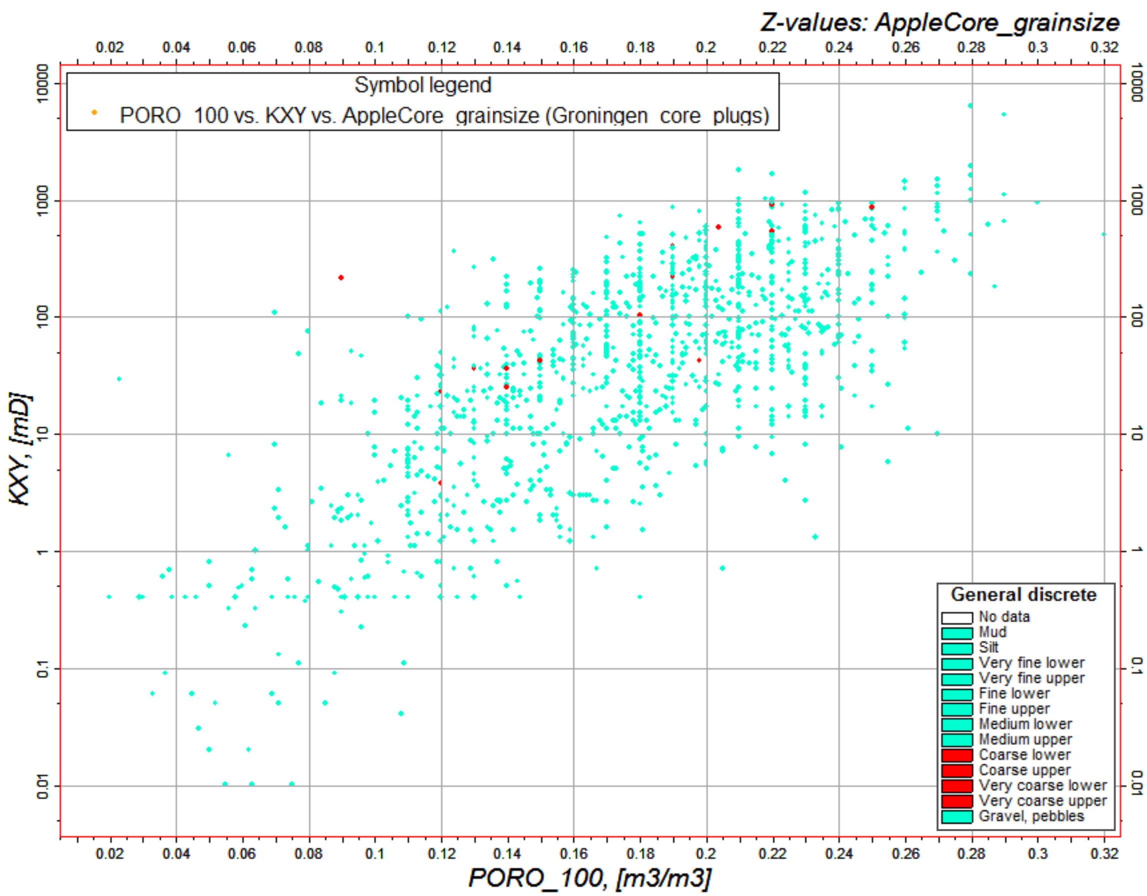


Fig. 23: Porosity-permeability cross-plot from core plug data, coarse to very coarse sandstone plugs coloured red

All grain size classes*

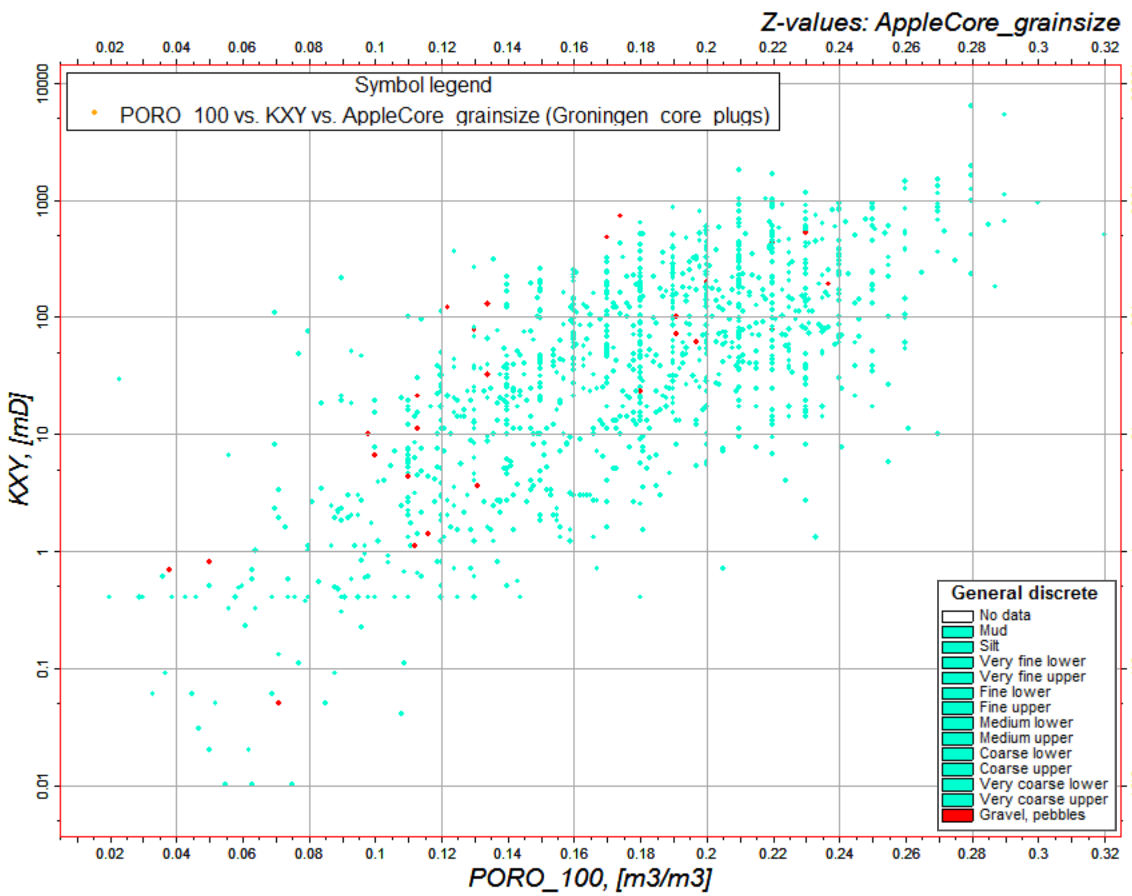


Fig. 24: Porosity-permeability cross-plot from core plug data, pebbly sandstone and conglomerate plugs coloured red

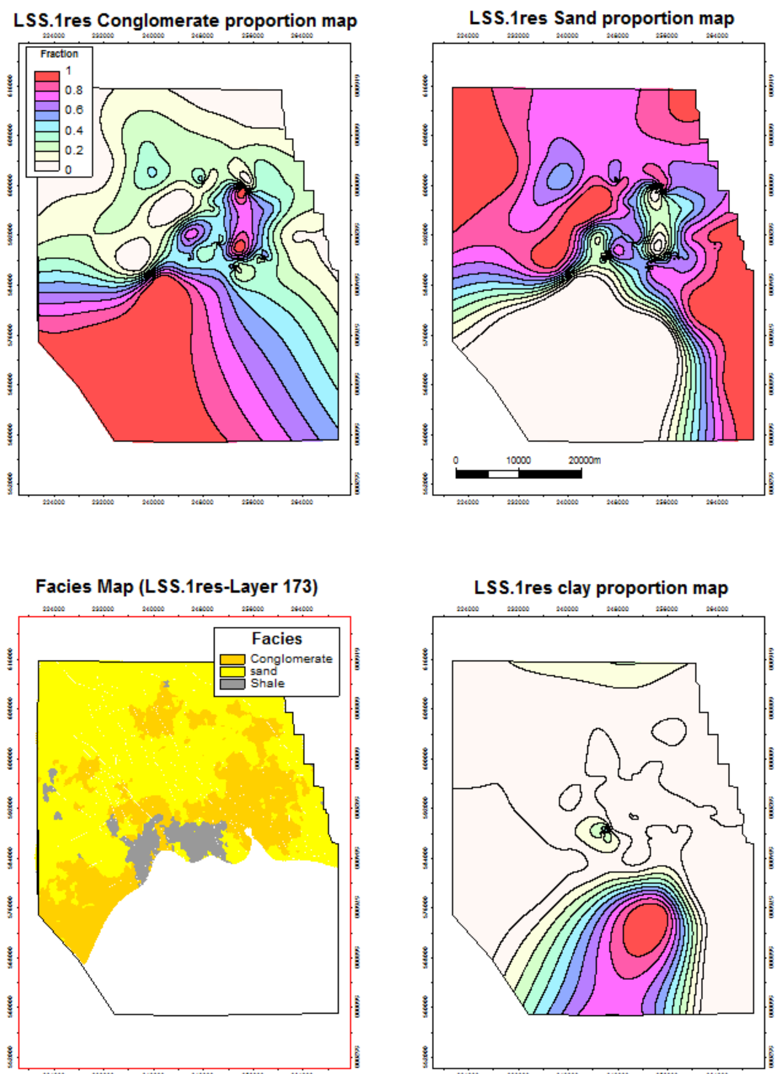


Fig. 25: Vertical proportion maps per electrofacies and one representative model layer for reservoir unit LSS.1res

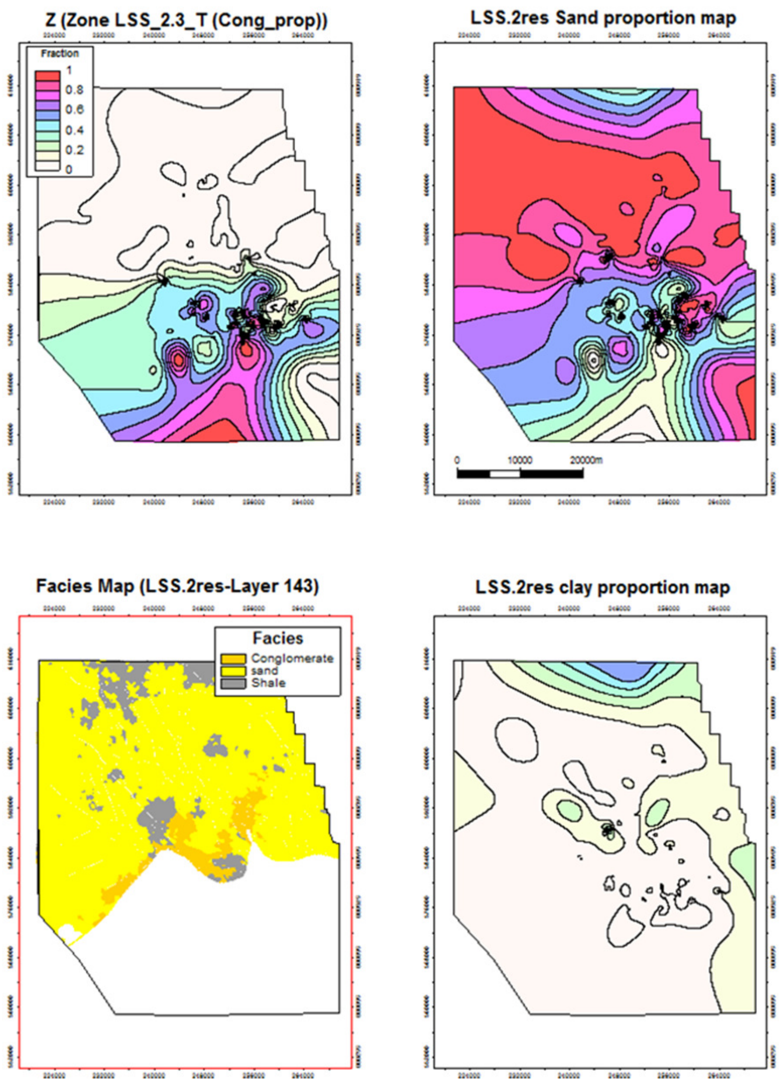


Fig. 26: Vertical proportion maps per electrofacies and one representative model layer for reservoir unit LSS.2res

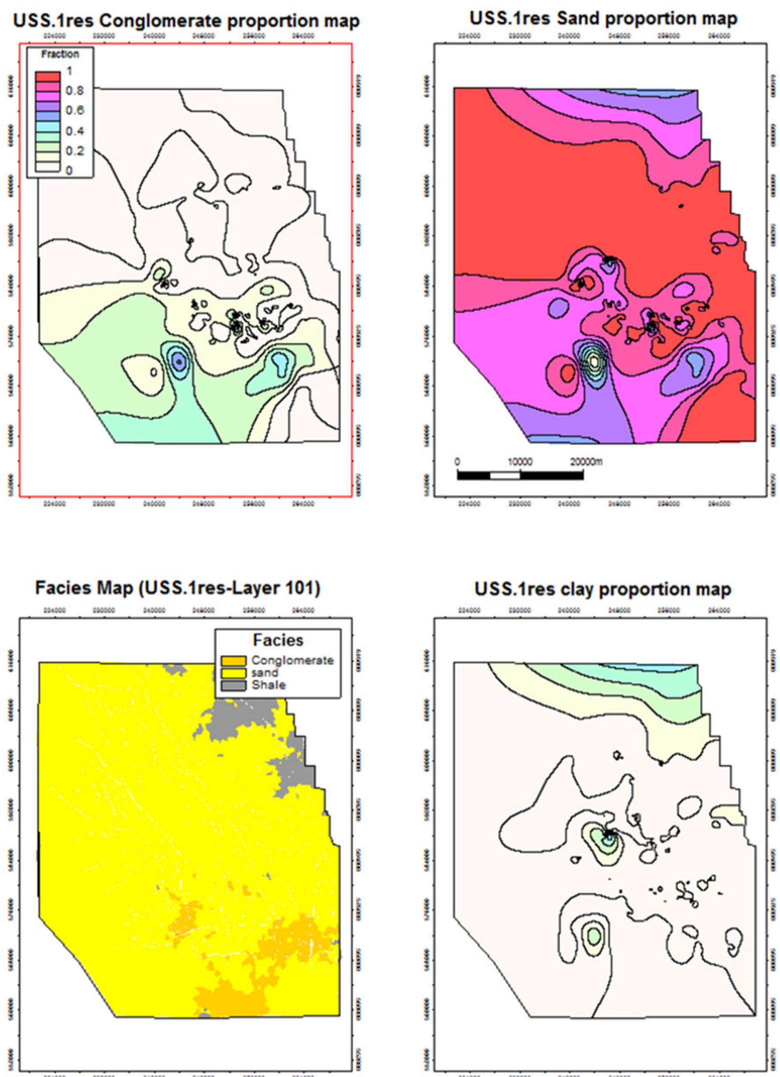


Fig. 27: Vertical proportion maps per electrofacies and one representative model layer for reservoir unit USS.1res

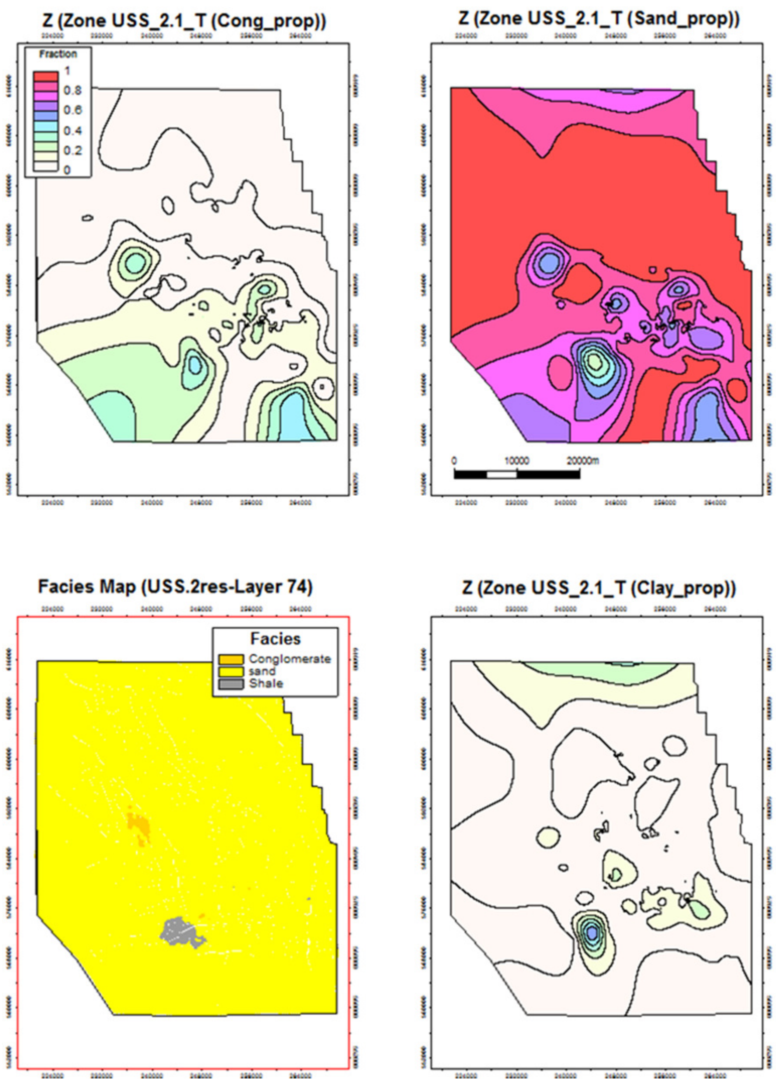


Fig. 28: Vertical proportion maps per electrofacies and one representative model layer for reservoir unit USS.2res

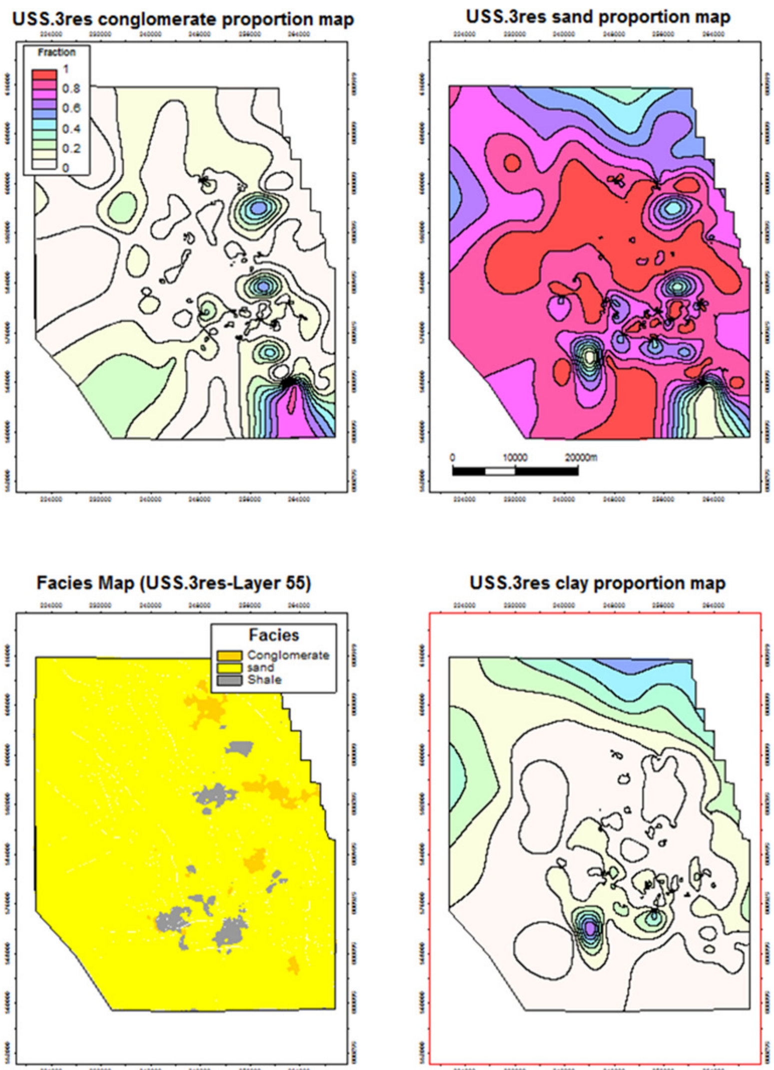
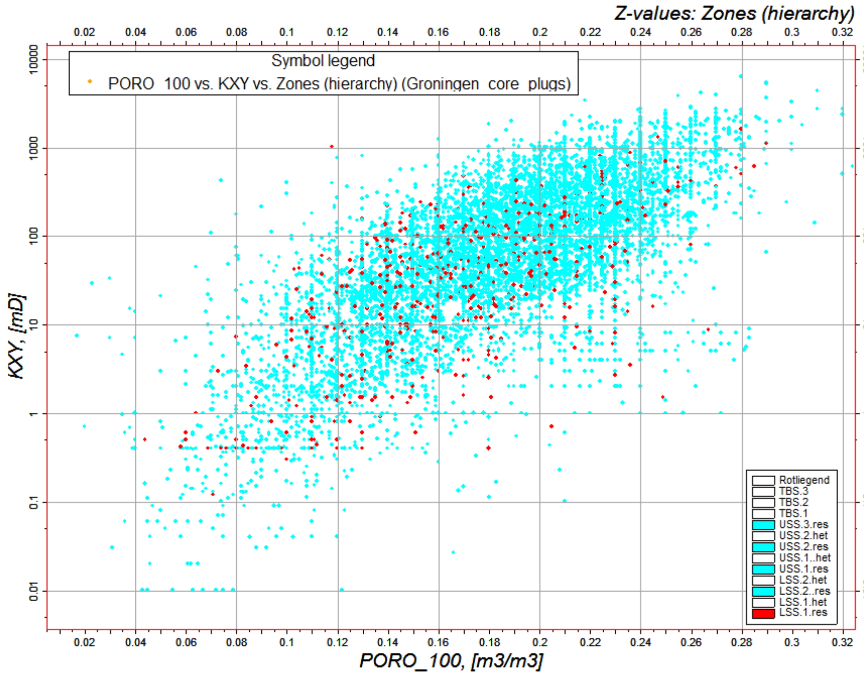


Fig. 29: Vertical proportion maps per electrofacies and one representative model layer for reservoir unit USS.3res

Plug data from reservoir zones only

All cored wells



Study wells only

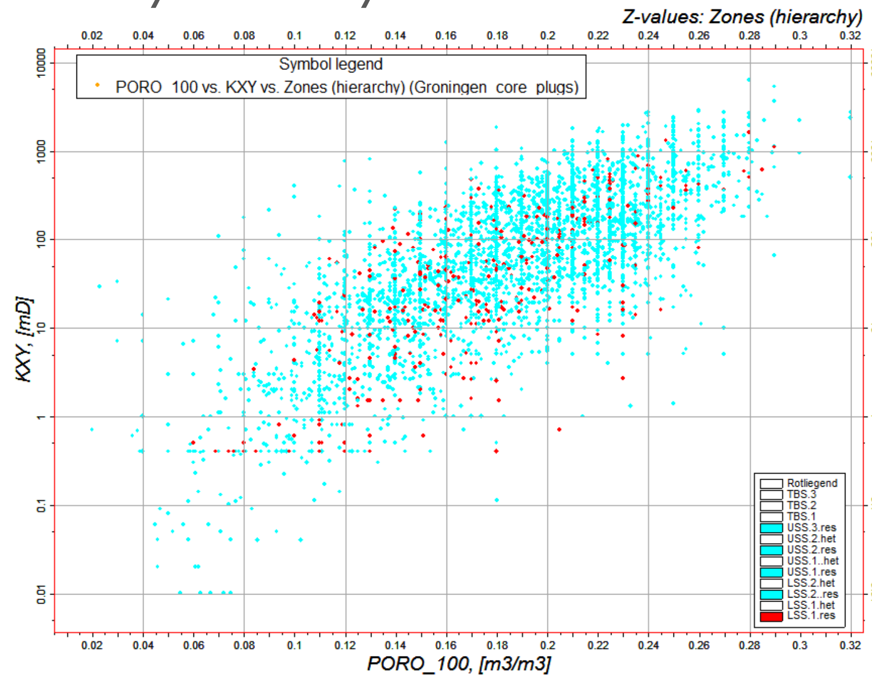
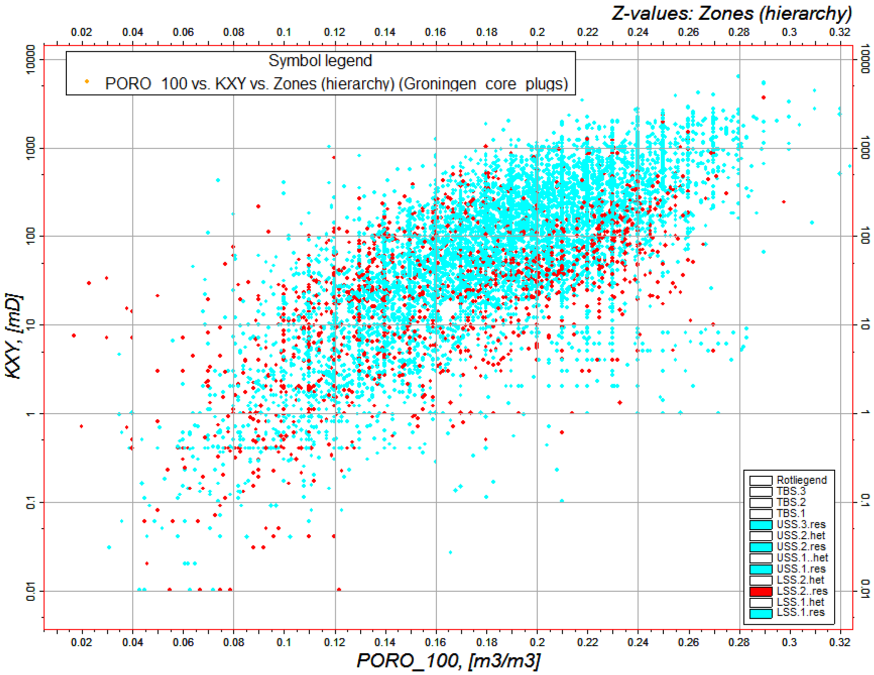


Fig. 30: Porosity-permeability cross-plot of core plug measurements, data points from LSS.1res coloured red. Left-hand graph shows entire Groningen plug database, right-hand graph shows data for study wells only.

Plug data from reservoir zones only

All cored wells



Study wells only

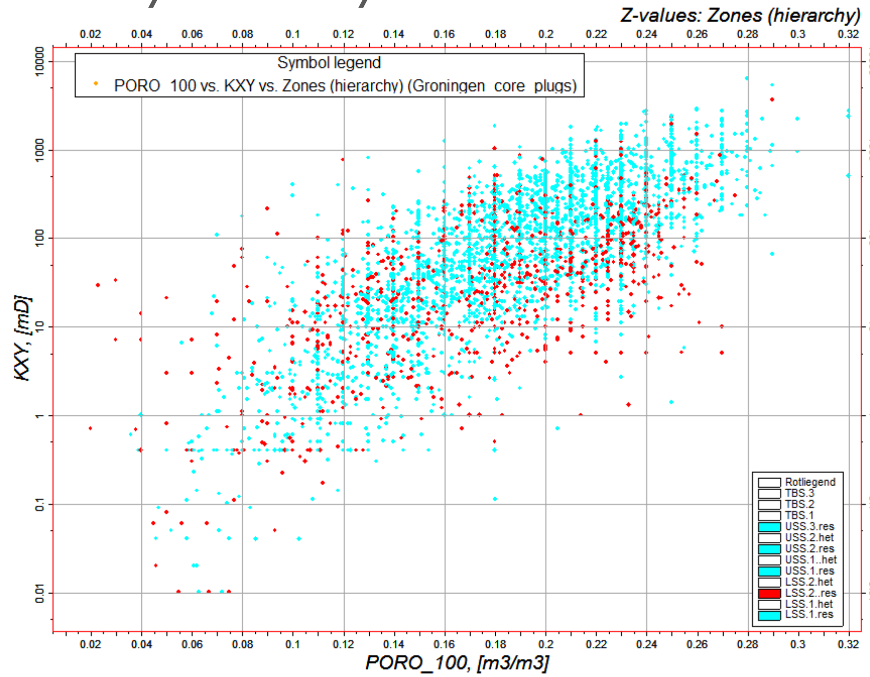
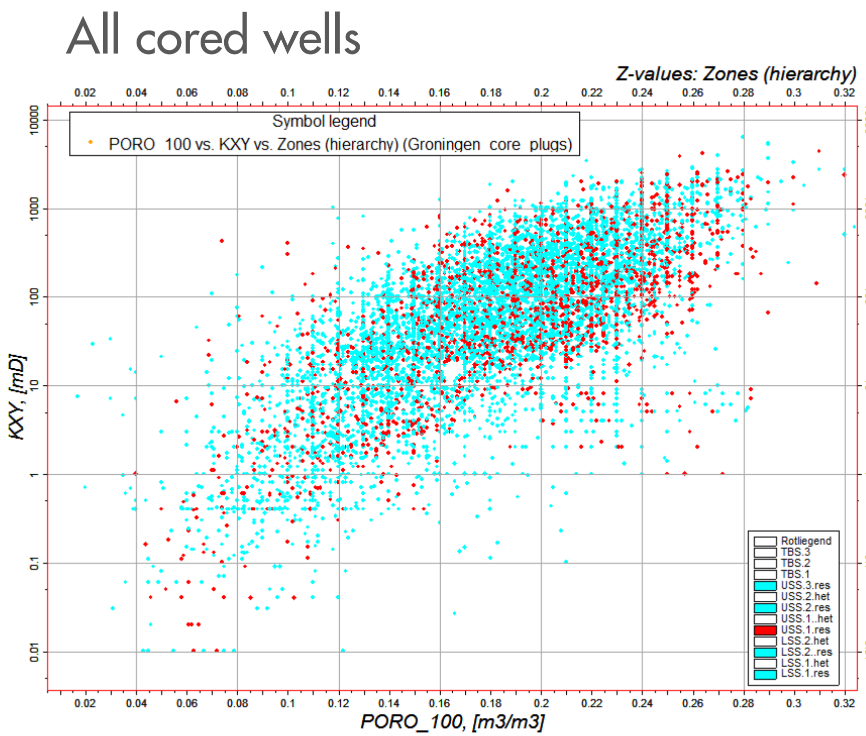


Fig. 31: Porosity-permeability cross-plot of core plug measurements, data points from LSS.2res coloured red. Left-hand graph shows entire Groningen plug database, right-hand graph shows data for study wells only.

Plug data from reservoir zones only



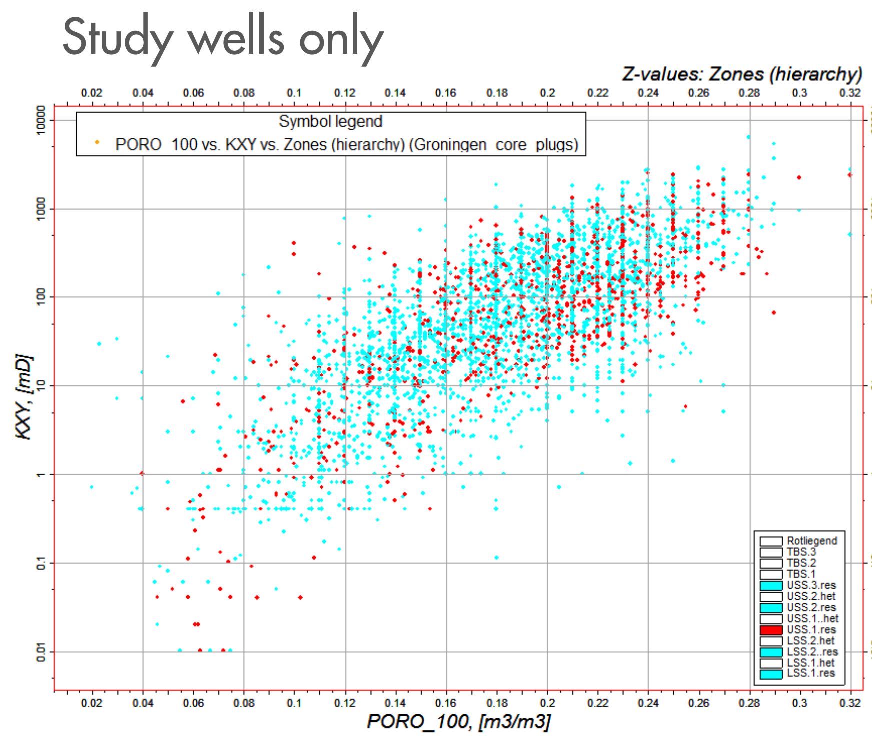
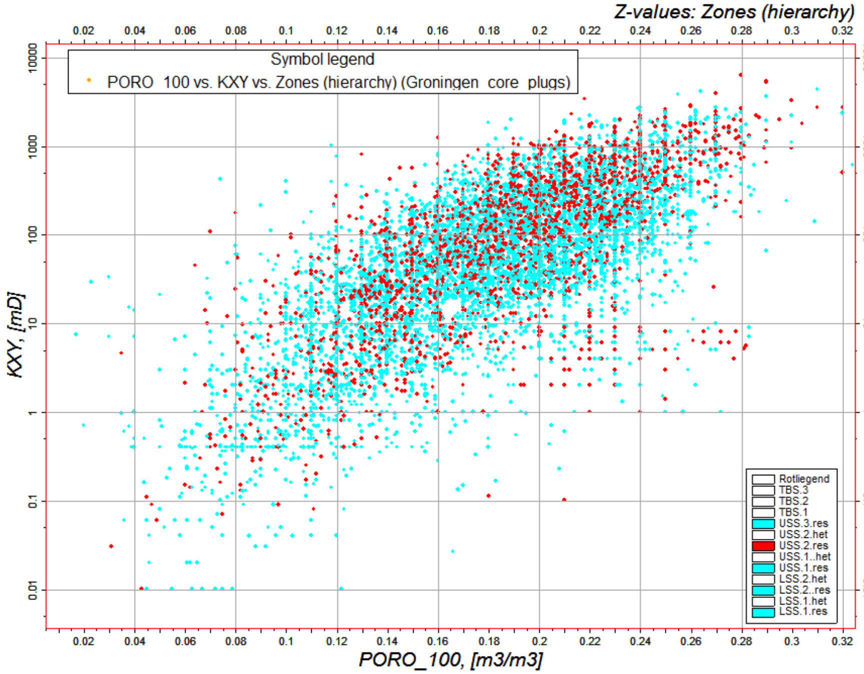


Fig. 32: Porosity-permeability cross-plot of core plug measurements, data points from USS.1res coloured red. Left-hand graph shows entire Groningen plug database, right-hand graph shows data for study wells only.

Plug data from reservoir zones only

All cored wells



Study wells only

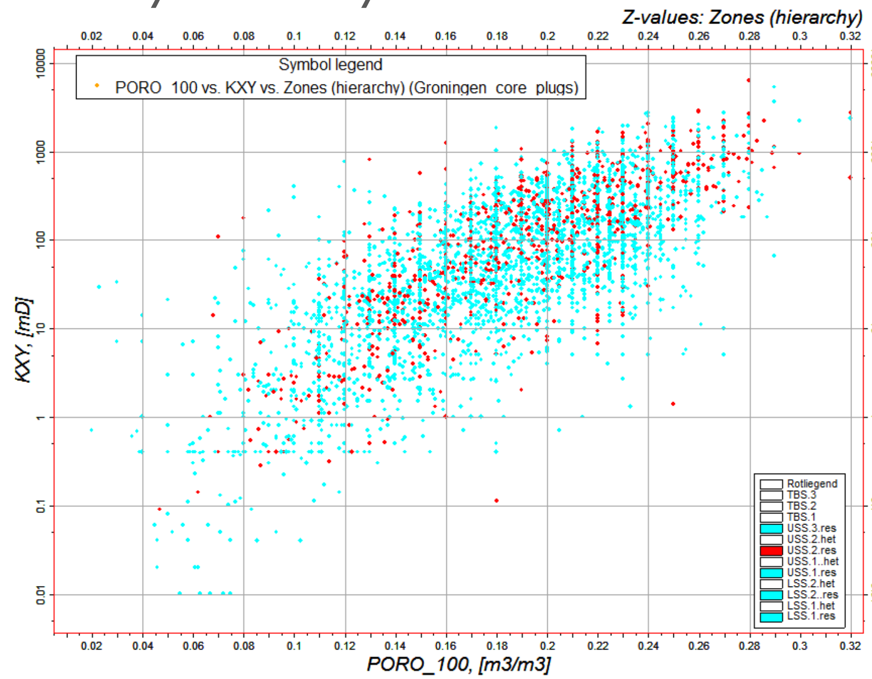
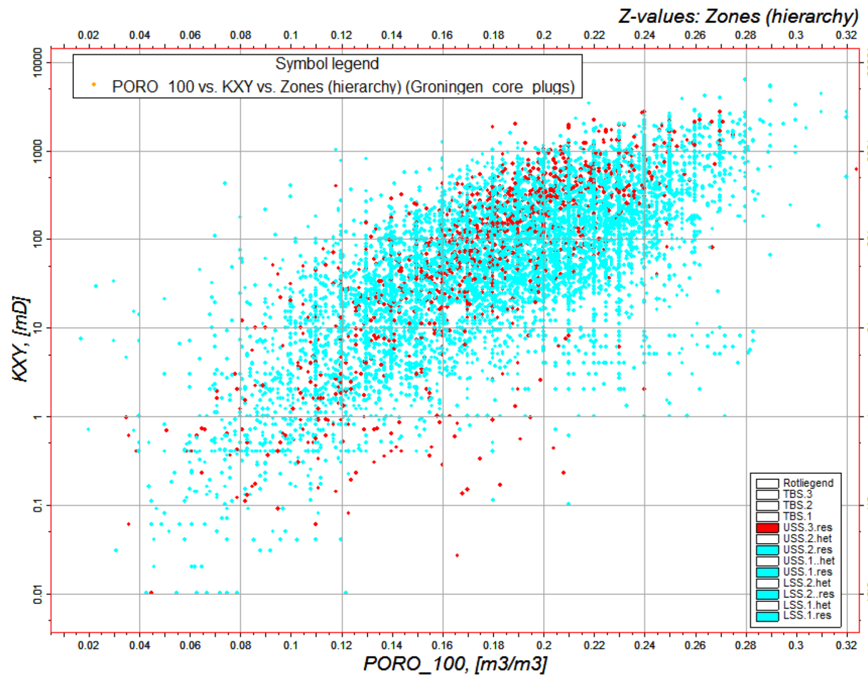


Fig. 33: Porosity-permeability cross-plot of core plug measurements, data points from USS.2res coloured red. Left-hand graph shows entire Groningen plug database, right-hand graph shows data for study wells only.

Plug data from reservoir zones only

All cored wells



Study wells only

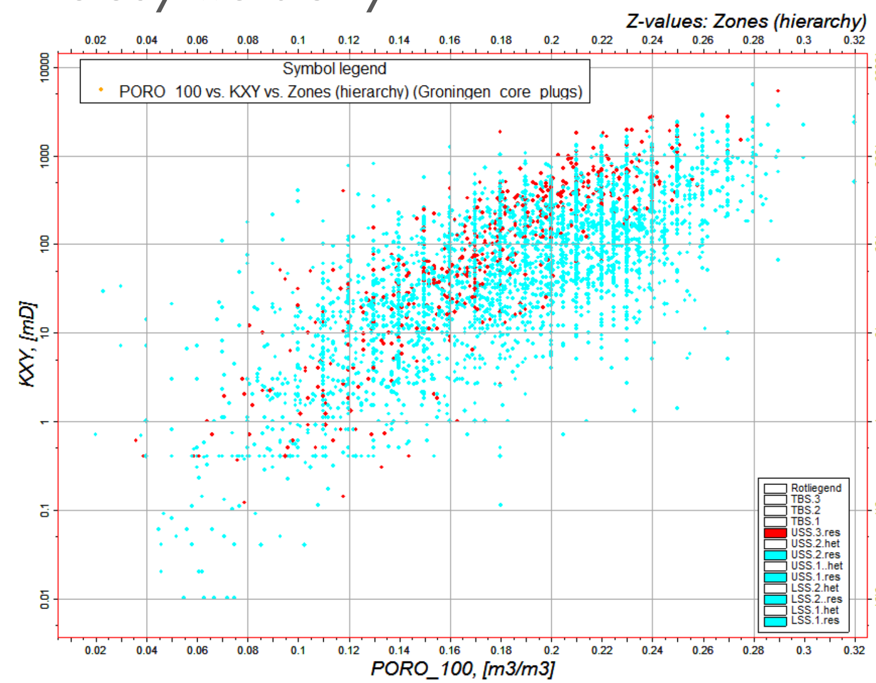


Fig. 34: Porosity-permeability cross-plot of core plug measurements, data points from USS.3res coloured red. Left-hand graph shows entire Groningen plug database, right-hand graph shows data for study wells only.