Oil & Gas Science and Technology – Rev. IFP, Vol. 57 (2002), No. 4, pp. 311-340

Stratigraphy and Oil: A Review

Part 2

Characterization of Reservoirs and Sequence Stratigraphy: Quantification and Modeling

Ch. Ravenne[1]

1 *Institut français du pétrole, division Géologie-Géochimie, 1 et 4, avenue de Bois-Préau, 92852 Rueil-Malmaison Cedex - France*
e-mail: christian.ravenne@ifp.fr

Résumé — Stratigraphie et pétrole : bilan – Deuxième partie : Caractérisation des réservoirs et stratigraphie séquentielle : quantification et modélisation — Cet article est le second d'une série de deux articles qui porte sur l'ensemble de l'activité de recherche entreprise par l'auteur à l'*IFP* depuis 1972, dont le fil conducteur a été la stratigraphie, qu'elle soit sismique ou séquentielle.

Cette série est composée de quatre chapitres résumant les résultats importants des travaux effectués, avec une insistance particulière sur ceux qui ont une portée méthodologique. L'ordre chronologique a été conservé pour souligner l'évolution des idées et des méthodes.

Le premier article (Ravenne, 2002) comportait les trois premiers chapitres. Le premier chapitre sur l'étude des marges actives du sud-ouest Pacifique comportait déjà les prémices de la stratigraphie sismique. Le second traitait de l'introduction, en France, de l'essor et de la diffusion de la stratigraphie sismique. Le troisième concernait l'étude des cônes détritiques sous-marins avec la large utilisation des méthodes de la stratigraphie sismique, les interactions entre les apports des travaux à terre et ceux de sismique marine, et enfin, l'application des expériences en canal et en cuve, destinées à l'interprétation des dépôts gravitaires. Ces résultats auront une influence importante sur le développement de la stratigraphie séquentielle.

Ce second article (quatrième chapitre) montre la puissance de l'outil « stratigraphie séquentielle » pour la caractérisation des réservoirs pétroliers et gaziers. Cette période d'activité (la plus longue et qui a impliqué le plus de chercheurs) s'est traduite par le développement d'une géologie quantitative et par la création de méthodes et de logiciels permettant l'utilisation directe des connaissances géologiques. Elle a été marquée par l'instauration d'une pluridisciplinarité effective et efficace. Dans ce chapitre, le rôle moteur que l'*IFP* a tenu dans le renouveau de la sédimentologie et de la stratigraphie en France est souligné.

Chacun de ces chapitres comporte une introduction qui présente l'état des connaissances à l'époque où les travaux ont été entrepris ainsi que les enjeux des recherches, un paragraphe sur les travaux réalisés et un autre dédié aux principaux résultats.

Les perspectives des travaux futurs concernant les actions de recherche et de développement qui pourraient être entreprises sont présentées avec les principales conclusions.

Abstract — Stratigraphy and Oil: A Review – Part 2: Characterization of Reservoir and Sequence Stratigraphy: Quantification and Modeling *— This article is the second of a series of two covering all of the author's research activity at* IFP *since 1972, of which the main focus has been stratigraphy, seismic as well as sequential.*

This series is composed of four chapters resuming the important results of the work done and stressing those that have a methodological scope. The chronological order is preserved to emphasize the evolution of ideas and methods.

The first article (Ravenne, 2002) contains the first three chapters. The first chapter of the study of the active margins of the Southwest Pacific already contained the basics of seismic stratigraphy. The second dealed with the introduction, growth and spread of the seismic stratigraphy. The third addressed the study of submarine fans with the broad use of the methods of seismic stratigraphy, the interactions between the inputs of onshore studies and marine seismic studies, and the application of channel and tank experiments to the interpretation of gravity deposits. These results had a significant impact on the development of sequential stratigraphy.

This second article (fourth chapter) demonstrates the power of sequential stratigraphy for the characterization of oil and gas reservoirs. This period of activity (the longest and which involved the largest number of researchers) resulted in the development of a quantitative geology and the creation of methods and software allowing the direct use of geological knowledge. It was marked by the establishment of a real and effective multidisciplinarity. In this chapter, the driving role that IFP *played in the renewal of sedimentology and stratigraphy in France is emphasized.*

Each of these chapters contains an introduction presenting the state of knowledge at the time when the work was undertaken and the challenges facing the researchers, a section on the work done, and one of the main results achieved.

Prospects for future work concerning research and development that could be undertaken are presented with the main conclusions.

1 SEDIMENTOLOGY, STRATIGRAPHY AND RESERVOIR CHARACTERIZATION

Everything presented here is the outcome of the work of the project team "Production Geology" led by the author from 1985 to 1996. A large share of the activity was the development of the method for studying reservoir systems.

1.1 Introduction

The reservoir simulation methods still used in the late 1980s were of the "layer-cake" type, which made use of porosity-thickness and permeability-thickness maps to characterize each of the blocks of the grid of the model. Data such as lateral continuity, and permeability barrier, were often poorly known.

One of the difficulties encountered by the reservoir engineer in using simulation models stems from the fact that oil reservoirs are natural environments whose physical properties are virtually always heterogeneous and anisotropic at all scales. In fact, the heterogeneity of the reservoirs is one of the most important causes of the difficulties or failures of oil recovery methods. Experience has shown that in most cases, this heterogeneity could not be suitably described only on the data from widely spaced wells.

Hence the knowledge of the heterogeneities was and still is an essential factor in optimizing the development of reservoirs. It allows the choice of an appropriate mathematical model to represent the reservoir, a model that serves to propose consistent lithofacies between the available wells. At the start of the project, a strong demand for the knowledge of these reservoir heterogeneities emerged, as emphasized by numerous researchers (Weber, 1986, Lasseter *et al*., 1986) and several symposiums and conferences held previously or during the execution of the project ("Reservoir Characterization Technical Conference", NIPER 1985, Dallas; the special sessions of the 62nd and 63rd "Annual Technical Conference and Exhibition of the Society of Petroleum Engineers *(SPE)*", Dallas 1987 and Houston 1988; symposiums on the Characterization of Reservoirs organized by the *SPE*, Durango, United States, 1987, Grindelwald, Switzerland 1988. Subsequent studies are not included because they became too numerous as other teams converged on the problem. Geostatistics only appeared very seldom in these meetings (one or two papers out of fifty). Three years later, practically no papers failed to mention geostatistics, and it is often very poorly used, lacking support from solid ground data.

One of the originalities of the *IFP* team was to really work in common between geologists and geostatisticians, and thereby define the data acquisition mode. The creation of a common language was a lengthy process (more than two

years) and after this, it was necessary to persuade the researchers of the two teams to work together. This multidisciplinarity achieved engendered requests from the companies on the way to organize joint working groups which were not merely "collages" of specialists, with the geologists supplying the results of this interpretation to the geostatistician who transmitted the results of this calculations to the reservoir engineer. Another outcome of this cooperation was a different field approach by surveying unbiased sections, in other words, permitting a valid statistical approach, which was impossible with the sections surveyed with the sole aim of understanding the sedimentary system, and which are still made in specific contexts.

The knowledge of reservoir heterogeneities had not evolved much in the last fifteen years preceding the initiation of this project. There were many reasons for this delay: few geologists were attracted by field observations at the scale of the reservoir, and even less knew how to handle the change of language required to transform the purely geological description into quantified data permitting the description of the reservoirs. It demands a combined effort of discretization into subunits (such as layers or blocks) and the attribution of different pertinent physical properties to these subunits. Geostatistics is involved here because, as widely acknowledged later, it was the necessary tool and link between the geologist and the reservoir engineer. However, it was only employed at this scale where it was indispensable (where the available information was limited) and followed a first sequential breakdown established with the deterministic model used up to its limits. The pioneering studies still mentioned were those of Montadert *et al.* (1966a and 1966b) and Verrien *et al.*, (1967) in the Sahara. The suspension of these studies appears to be linked to the prodigious development of data processing, which caused some reservoir engineers to feel that it would help to limit their reliance on geology particularly since it was not quantified.

To understand and predict the behavior of an oil reservoir implies a realistic geological description of the reservoir and the simulation of its behavior to predict the production rates that correspond to different operating methods. This task is difficult because the data in the possession of the reservoir engineer (cores, wireline logs, test wells, seismic surveys) offer a very limited knowledge of the reservoir due to the spacing of the wells, routinely several hundred meters (*Fig. 1*), or even a kilometer or more. A major problem was hence to interpolate between the widely spaced well data, and this interpolation had to be as realistic as possible to obtain a grid of petrophysical values for the flow simulation model. Figure 2 illustrates the type of standard correlation made by the reservoir geologists to satisfy the needs of the reservoir engineers, even if they had more precise ideas of the variations but could not demonstrate them.

As we shall demonstrate later, the solution proposed was that the answers to the problem of interpolation between the well data could be provided by the methods of sedimentology. In fact, reservoir heterogeneities are not distributed in an absolutely random manner. In sandstone reservoirs in particular, they are closely controlled by the depositional mode of the sediments making up the reservoir, even though some factors subsequently modify the porous medium and its physical properties. Note also that at the start of the project, there were no quantified geological data available, and new mathematical tools had to be developed for geological simulations.

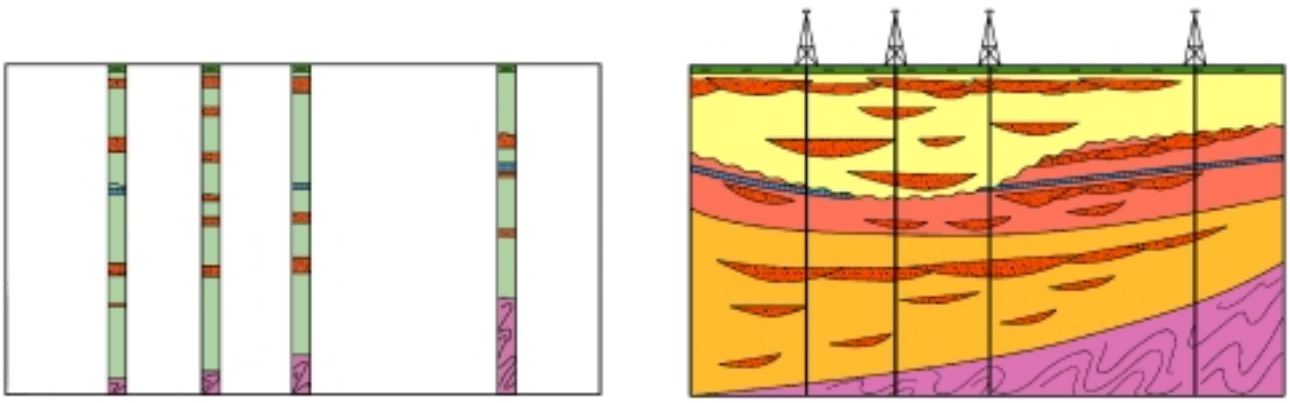

Figure 1

Problems encountered by the reservoir engineer (Ravenne and Galli, 1995a).

The well data in the possession of the reservoir are 1D and widely spaced. With these data, it is very difficult to reconstruct the real image (at right). At this scale (about 100 m thickness), only a rigorous sequence stratigraphy and high resolution analysis can help to differentiate between the genetically homogeneous series, to evaluate the hiatuses and erosion unconformities, and to identify the marker horizons of the deposition paleohorizontals.

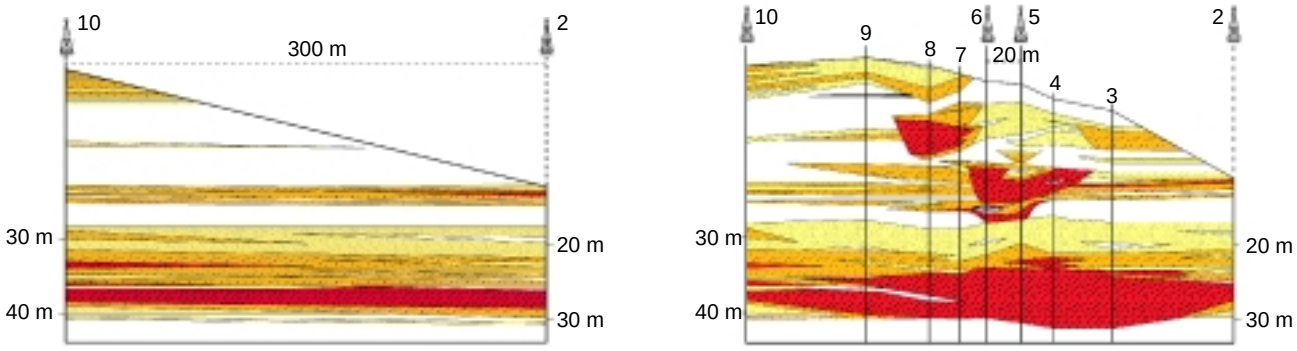

Figure 2

Example of conventional "layer-cake" type of correlation to be compared with the real section (Ravenne and Galli, 1995a).

Wells 2 and 10 (at left) were supplied to reservoir geologists of five different companies. They all more or less made the correlations shown in this diagram, most of them being aware that these correlations did not reflect reality. However, lacking any means to quantitatively justify more thorough interpretations, in order to satisfy the next user (the reservoir engineer), they had to furnish this type of correlation to supply the "layer-cake" models. The image at right corresponds to reality (nine wells plus the image of the cliff located 10 m before the well line). Note the considerable increase in good reservoirs (clean sandstones shown in red), including the appearance of two levels that were previously nonexistent. This type of prediction is nonetheless possible with the analysis of the high resolution sequence stratigraphy data and the results can be quantified to supply stochastic models. The argillaceous sandstones are colored orange, silty clays are colored yellow and clay is colored white.

1.2 Aim of the Project and Challenges

The aim was to describe, at metric to hectometric scales, the heterogeneities of reservoirs significant of different depositional environments, from the outcrop and well data (cores and/or logs), and then to take account of the dynamic and seismic data. This description had to rely on the construction of topo-probabilistic models constrained by these different data. The *IFP-ARMINES* team was the first to deal with this problem successfully thanks to the synergies developed:

– More ambitiously, the aim was to introduce the geology and particularly the sedimentology and stratigraphy into the reservoir models. The reservoir engineers use grids of numbers, and the first problems arising were hence the quantification of our results and the choice of the parameters.

– It was then necessary to overcome the resistance of vested interests.

  For the geologists, from the outset and for several years, many colleagues of different companies repeated to us that the work done was going to "kill" geology by supplying reservoir engineers with such tools. What happened was exactly the opposite: the project helped to provide very detailed field studies to meet the needs of the reservoir engineers and to upgrade the core studies. It was demonstrated that the essential tool for completing this project was sequence stratigraphy which allows the understanding and quantification of the systems investigated. One of the results of the project was to improve and develop new concepts in sequence stratigraphy.

  For the reservoir engineers, they were very satisfied with the aim of the project, but above all, did not want the geologists to be involved in the subsequent use of the models proposed! Hence the third challenge:

– The establishment of a real multidisciplinarity and hence a common language. We will show below that this was a lengthy and complicated process, but finally succeeded.

– Finally, the idea was to develop new methods and new tools and make them known to the international community. Curiously, this recognition was obtained very quickly and was also very soon followed by fierce competition.

1.3 First Studies Made: Yorkshire, United Kingdom, Middle Jurassic

The first project, which was the most detailed, helped to develop the methodology for analyzing outcrops for the reservoirs, recognizing the errors to avoid repeating them in subsequent studies, and to optimize future studies. Special attention was paid to the high resolution sequence stratigraphy analysis of the outcrops, cores and logs, to gain a better understanding and predict the variations of the environment from the well data alone. To achieve this aim, a row of wells was drilled immediately adjacent to the cliff, thereby allowing a direct comparison of these three types of data. This helps to identify the keys for determination of the meandriform fluvial systems which were largely utilized subsequently in real case studies.

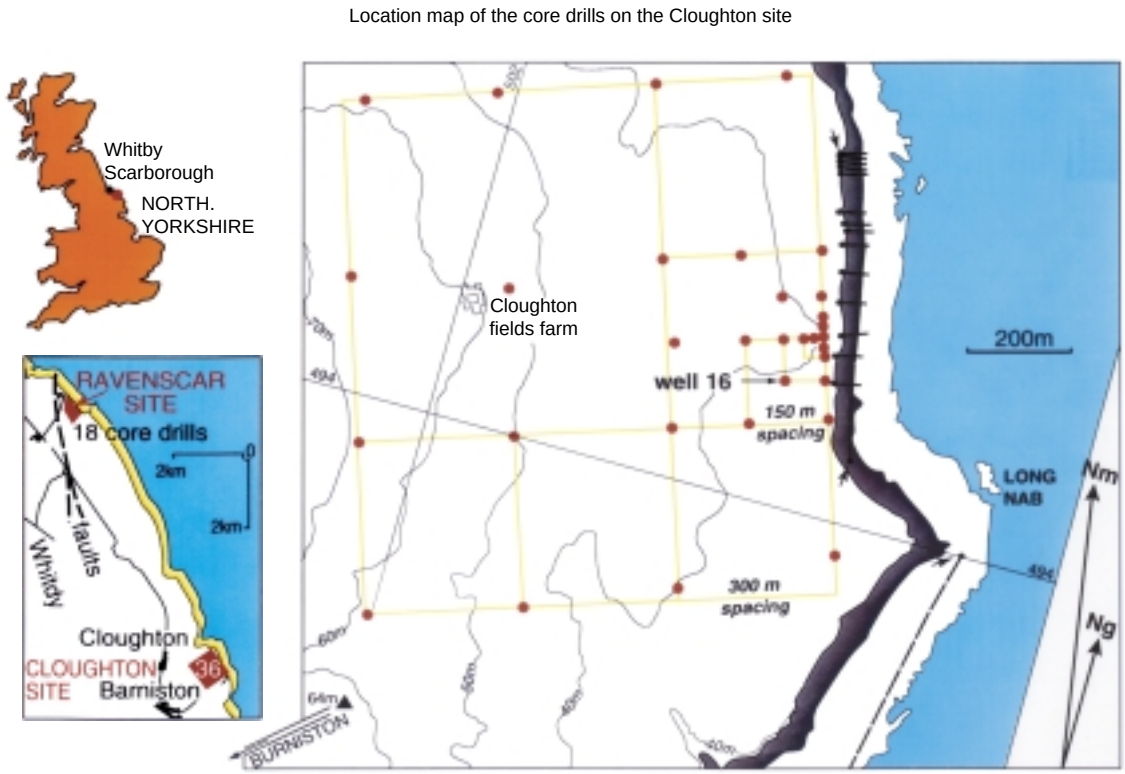

Figure 3

Position map of the Yorkshire sites (Ravenne *et al.*, 1989).

The two sites are located in the inset at the left hand bottom. The detailed Long Nab site, to the right, corresponds to the Cloughton site in the inset. The borehole grid is shown and the spacing in the mesh from the center to the East, immediately near the cliff, can be observed. The vertical sections surveyed in the cliff are indicated by black lines. Between the cliff and the open sea, the foreshore helps to observe the characteristics in plane view of the lower system.

Two sites measuring about one square kilometer each (*Fig. 3*) were investigated in this area: Long Nab and Ravenscar in two successive phases:

– field studies and then;
– construction of a geostatistical model.

The zone and age of the formations investigated corresponded to two requirements:

– A very high complexity of the fluvio-deltaic environment, which in case of success of the project, as the case turned out, ensured the possibility of extension and generalization of the method to other environments.
– The difficulty of predicting the short-distance evolution of the members of the Brent "Formation" (Formation is written in quotation marks because the five letters of Brent correspond to the subdivision of the North Sea Middle Jurassic into five lithostratigraphic formations: Broom, Rannoch, Etive, Ness, Tarberg (Deegan and Scull, 1977; Vollset and Dore, 1984). The cliff selected and the two sites represent the only correct and complete analogues (age and environment) of this Formation. Eschard *et al.* (1993) demonstrated that this was a source of error and that these members were diachronous. This is fully acknowledged today, but this subdivision clearly reflects the problems of the time with the habits of litho-stratigraphic correlation which certainly facilitated the work of the reservoir engineers, by enabling them to calculate the petrophysical properties on relatively homogeneous units. This further emphasizes that the geologic knowledge was barely taken into account by the "downstream" users: lack of communication, lack of means of communication (lack of quantified data) and probably inappropriate to the needs or insufficient. The reservoir engineers were aware of the need to introduce more geology into their model, but, for example for Brent in the North Sea, the geologists could supply considerably different interpretations from one another, and therefore unusable, so that the channel elongations were claimed to trend north-south by one group and west-east by another.

These two sites are characterized by the presence of a sandstone dominant in the Long Nab site and argillaceous dominant in the Ravenscar site.

The series examined in the Long Nab site corresponds to the Scalby Formation (Bathonian). This series was first deposited in an estuarine valley fill environment for the lower unit and then in a deltaic plain environment for the upper unit. The Formation is separated from the marls and marine sandstones of the underlying Scarborough Formation by an erosive unconformity of regional scale. The top of the Scalby Formation is eroded by Quaternary glacial deposits.

The series examined in the Ravenscar site corresponds to the Ravenscar Formation (of which the Scalby Formation is the uppermost term) which extends from the Aalanian to the Bathonian. The data acquired enabled Eschard (1989) to show that high resolution sequence stratigraphy is predictive concerning the spatial location of the sedimentary bodies and their geometry in the depositional sequence. This was confirmed by all the studies made subsequently by the team, and helped to persuade numerous researchers and engineers of the power of this method.

The 10 km of the cliff were photographed continuously and detailed views were taken of each of the two sites (*Fig. 4*). A preliminary interpretation of the outcrops of each was established by using these photographs and a series of vertical sedimentological sections back-surveyed on a doubled rope in the cliff. The spacing of these sections was determined with geostatisticians in order to optimize the use of the data. The detailed analysis of the photographs of the Long Nab site served as support for a mathematical morphological analysis.

Thirty-six boreholes, each 25 to 50 m long, were drilled and cored continuously on the Long Nab site (*Fig. 3*). About 1100 m of cores were thus collected. Eighteen boreholes, about 50 m length each, were drilled and cored continuously on the Ravenscar site. Five boreholes were prolonged to 150 m in order to clarify the vertical extension of the simulations. 1400 m cores were obtained. Here also, the layout and spacing of the boreholes were selected with the geostatisticians. Wireline logs, specially gamma-ray and dipmeter logs, were recorded in each borehole. Porosity and permeability measurements were taken on the samples on the cliff and on the samples taken at 20 cm intervals in the reservoir environments of the cores.

The correlation tests between boreholes with the radar and seismic profiles were a failure. Problems of authorization led to a belated consumption of the geophysical data by radar waves, and this happened in a very humid and therefore very unfavorable period because radar waves are strongly absorbed by water and penetration was extremely reduced. Tests with multiple coverage processing were carried out. A significant improvement in the signal-to-noise ratio was obtained, but penetration never exceeded 10 m so that the objectives of the study could not be achieved. Two seismic surveys with explosives on the Long Nab site and weight dropping on the Ravenscar site were then carried out. The whole range of processing available was applied, but this also failed because of the insufficient thickness of the "overburden" above the survey zones. Hence while the result was negative, it subsequently helped to account for this problem and hence to pay close attention to the need for a sufficient thickness of "overburden" for any high resolution seismic survey.

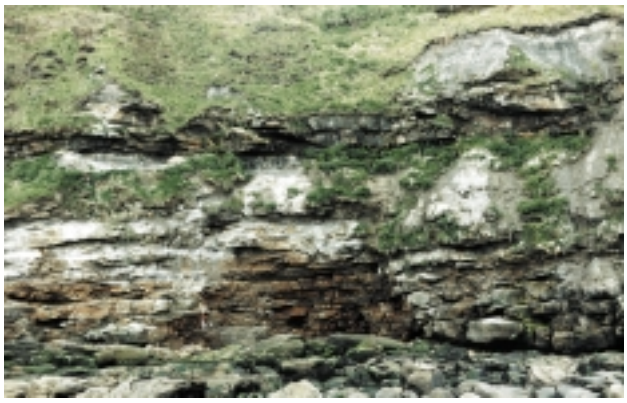

Figure 4

Alternating channels and alluvial plain in the Long Nab site (Ravenne *et al.,* 1989).

The vertical scale is given by the 2 m bar (alternating white-red-white-red) in contact with the lower bar (amalgamated fluvial channels of the prism I) and pebbles. The upper bar corresponds to prism III, see next figure.

1.3.1 Main Results of Phase 1: Analysis of Site 1 Field Data

The lower unit of the Scalby Formation was interpreted as a fluvial to estuarine filling of a paleovalley excavated during a relative fall in sea level. At the regional scale, it consists of three prisms of deposits of kilometric extension and decametric thickness *(Fig. 5)*. These prisms are separated by erosion surfaces. The geometry in superimposed sandy layers appears to have been promoted by a low subsidence rate of the basin, which allowed lateral migration of the distributary channels. The bottom prism is formed by the nesting of rectilinear fluvial channels with sandstone fill. The median prism is formed by several clay-sandstone meandering belts. The upper prism is formed of two silt-clay meandering belts. The influence of the tides, discrete in the first prism, is pronounced in the second and becomes preponderant in the third. It appeared to us to indicate a progressive rise in sea level and our subsequent investigations (Eschard *et al.,* 1991) emphasized this fact in the estuary filling phases.

The upper unit was interpreted as a deltaic plain environment overlying palustrine levels. The survey of these levels at reservoir scale is extremely important: all the geostatistical calculations were made with respect to positional paleohorizontals and the survey of such levels, or

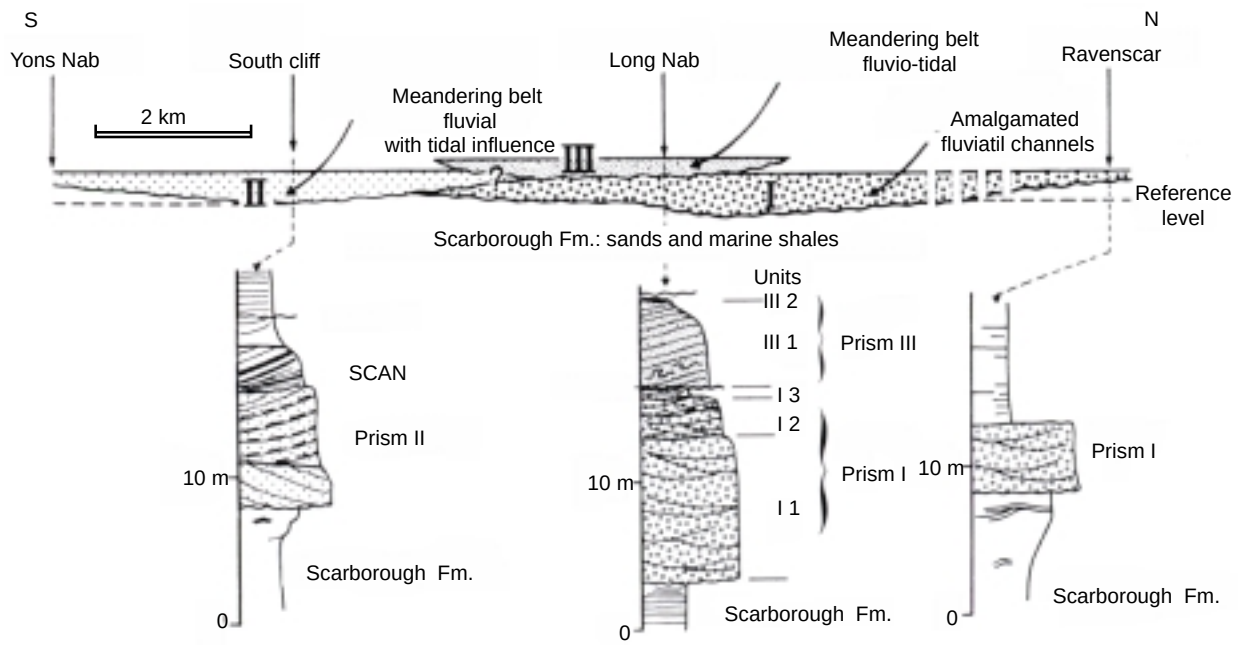

Figure 5

Diagram showing the layout of the three depositional prisms of the Scalby Formation (Eschard, 1989).

The Long Nab site, showed in greater detail here, corresponds to the central portion and only displays two of the prisms making up the Scalby Formation. The distance between Long Nab and Ravenscar is much longer than shown (white intercalations).

of paleosols, or even of onlap surfaces, is crucial for carrying out meaningful calculations. These calculations require a very detailed sedimentological and sequential stratigraphic analysis. Meandering or sinuous decametric channels are isolated in clay flood plain facies, which appears to affect the aggradation of a deltaic system during a relative high sea level period.

The geometry of the channels evolves steadily with cycles of relative variations in sea level, hence the importance of the high resolution sequence stratigraphy studies, and this result also reveals that one cannot use a single typical channel model for the modelings, especially Boolean. Yet this is a frequently encountered habit, which incurs serious errors in the exploitation of the reservoirs.

The results obtained apply not only to the sequence stratigraphy but also to the method of analyzing outcrops to characterize the reservoirs. This was the first time that all the techniques used jointly were implemented. Significant progress was achieved in the sedimentological and stratigraphic interpretation of the logs. This method was presented at several conferences (Ravenne and Beucher., 1988a; Ravenne *et al.*, 1988b, 1989, 1991) and the author was subsequently often consulted by a number of French and foreign companies for similar subsequent studies. This method has naturally evolved with the study of new outcrops, particularly for the use of photographic cliff data and their thickness restitution. In fact, the first morphomathematical technique proved to be very cumbersome and gave way to the construction of pseudo-wells, first very numerous (in a subsequent study—Trias of Almedina in Spain, 1989-1991—many thousands were necessary! (*Fig. 8*). They were then limited to the necessary number (several tens to a hundred) to characterize and obtain the quantitative parameters to be introduced into the models. These results also helped to establish a quantified database relying on the concepts of sequence stratigraphy.

1.3.2 Main Results of Phase 2: Construction of the Geostatistical Model

The development of the simulation method required the completion of the following steps:

- determination of simplified geological sections;
- analysis of the lithofacies distribution;
- variographic analysis of lithofacies;
- implementation of the simulation method;
- conversion of the lithofacies and change of scale;
- test of the model.

Establishment of Simplified Geological Sections

Two approaches were tested: first, the use of morphomathematical tools which, relatively ineffective at the time, entailed a lengthy and meticulous study. The second was the establishment with pseudo-wells: this approach, which is much faster, is only effective after having determined the number of pseudo-boreholes to be digitized to analyze a site.

Analysis of the Lithofacies Distribution

A tool was created: **proportion curves** (Ravenne and Beucher, 1988a; Ravenne and Galli, 1995a; Ravenne *et al.*, in publication). Initially this tool was only intended to serve for processing quantified data to make simulations, in other words, simply a statistical tool helping to constrain the simulations by really taking account of the geological data. It will be demonstrated below that this is an extremely powerful tool both for sequence stratigraphic interpretation and for correlations.

Two main families of proportion curves can be calculated, vertical and horizontal *(Fig. 6)*. The vertical proportion curve is a cumulative histogram of the proportions of each facies calculated line by line (or plane byplane) parallel to the datum level. The horizontal proportion curve is a projection on the horizontal line of the proportion of each facies cumulated well by well. They are calculated for each depositional sequence. The order (3rd, 4th, 5th, etc.) of these sequences used depends on the degree of accuracy achieved in the definition of the datum levels. It also depends on the number and quality of the available data and the study objectives. The examination of the vertical proportion curves obtained at a given order often helps to reach a higher order by identifying one or more other possible datum levels that can serve for new calculations. This examination also helps to check the quality of the correlations in each of the wells and/or to test/discriminate different potential levels: in fact, the examination of all the proportion curves plotted in the accurately investigated sites emphasizes the evolution and sequence subdivision. If the result is noisy, no evolution clearly appears, and the correlation levels must be reviewed or a possible internal unconformity identified (the calculation

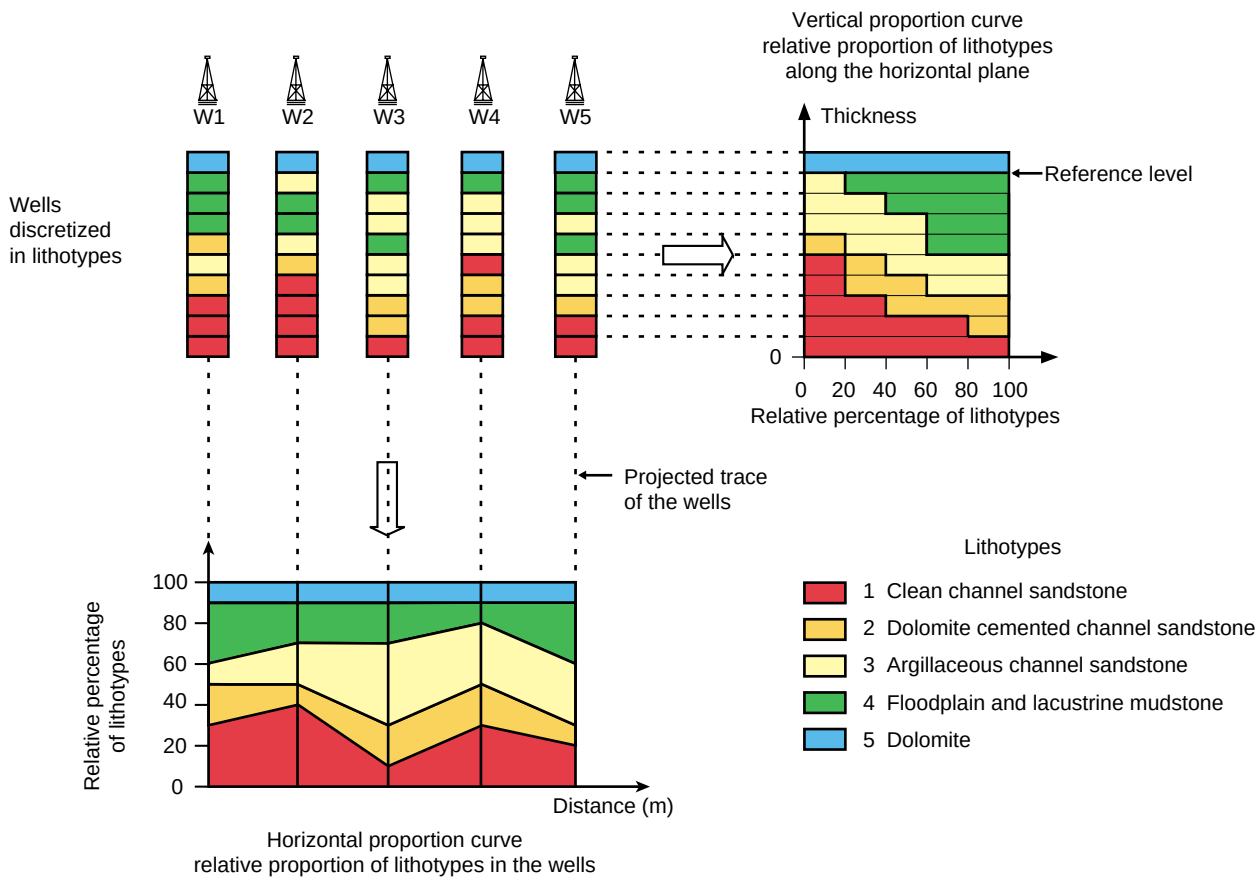

Figure 6

Horizontal and vertical proportion curves (Ravenne and Galli, 1995a).

At the top left are shown five wells discretized into lithotypes which serve to calculate the proportion curves. The case shown here is simple: isopach series without erosional unconformity either at the top or at the wall. The level that serves as a datum (deposition paleohorizontal at the scale of the site) is generally selected along a flooding surface, if possible maximum. The horizontal proportion curve (at bottom left) is calculated by summating the lithotypes along a vertical (in the sequence or unit analyzed) and ordered according to their appearance in the sequence. This curve helps to identify problems of correlation and the stationary or nonstationary character of the deposits. The vertical proportion curve is obtained by calculating the percentage of each lithotype level by level (parallel to the datum level).

is then made on several sequences), or the effects of possible differential subsidence must be tested.

This tool also helps to obtain information on the depositional environment. Thus on the proportion curve calculated, *(Fig. 7)* from the data gathered on the Almedina outcrop in Spain (Mathieu *et al.*, 1993; *Fig. 8)*, the upper portion represents the signature of a meandering fluvial system deposited in low accommodation rate environment, while the bottom portion corresponds to a meandering fluvial system deposited in a high accommodation rate environment.

The power of this tool was demonstrated for the validation and coherence of the database, for the determination of the chronostratigraphic markers to be used for the datum levels that would serve for the horizontalizations prior to the calculations (see Langlais *et al.*, 1993; Volpi *et al.*, 1997) and hence, therefore, for correlations of the sections or wells between one another. It is also a tool for sequence stratigraphic analysis that serves to quantify and visualize the lateral and vertical evolutions of the facies within the depositional sequences and which identifies the sequences of shorter duration.

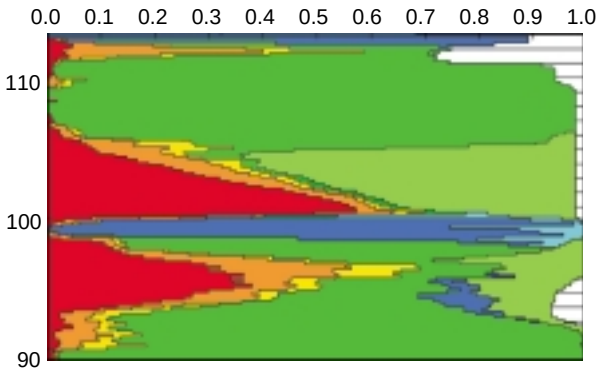

Figure 7

Signature on a proportion curve of two meandering fluvial systems deposited with different accommodation rates (Mathieu *et al.*, 1993).

The order and colors of the facies are as follows: red, clean sandstone, orange, argillaceous sandstone, yellow, silty clays, pale green, "plug" clays, dark green, alluvial plain clays, blue, lacustrine limestones. The unit between 95 and 100 m shows proportions of clean sandstones and argillaceous sandstones with a symmetrical shape about a horizontal axis at about 97 m. This signature is characteristic of meandering systems deposited during a period in which accommodation is high. The unit of the same facies of the portion between 100 and 107 m reveals a very asymmetrical form, with a very high proportion of clean sandstones from the contact with the limestones, which then steadily decreases. This signature is characteristic of amalgamated meandering systems deposited during a period of low accommodation.

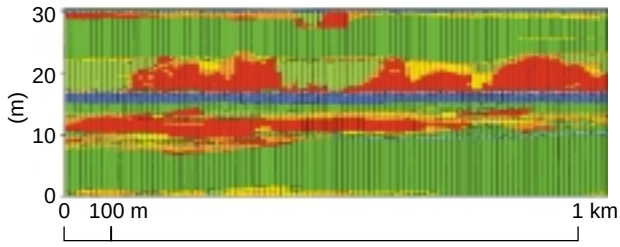

Figure 8

Ground section subdivided every 10 m into pseudo-wells (Mathieu *et al.*, 1993).

The field data were first quantified in detail to obtain a reliable database for different environments and for subsequent calculations of the proportion curves and variograms. The image shown here is an extract of the 4 km of cliff which were digitized every 4 km. This database served to plot the previous proportion curve (same key). Note that if only a few wells had been available, the correlation most frequently made of the upper unit would have revealed sandstone unconformities in the bottom portion and a plain summit displaying a clear contact with the clays. Here also, only a detailed analysis in facies sedimentology and sequence stratigraphy serves to differentiate between the "plug" clays and the flood plain clays, and to assign due importance to the lacustrine limestone level as the datum level.

Variographic Analysis of Lithofacies

The analysis of the individual variograms, horizontal and vertical, *i.e.* of those calculated for each of the facies of a given line or plane (always parallel—and if possible in the main anisotropy directions—or perpendicular to a deposition paleohorizontal), makes it possible, if these have been calculated with a sufficient information density, to characterize the component units of the reservoir qualitative and quantitatively, in space. In brief, the variogram is a mathematical function which gives the correlation between two points as a function of the distance between them. For some natural phenomena, a distance exists beyond which the two points no longer influence each other. This limit distance is called "range" of the variogram.

In the study of underground reservoirs, both aquifers as well as oil and gas pools, the low well density with respect to the volume analyzed only allows a detailed analysis of the vertical variograms. The well spacing, often several hundred meters, only offers an approximation of the range (one of the four parameters supplied by the variogram with the value of the sill, the type and the behavior at the origin; these four parameters are necessary for the modeling): the real range is often shorter than the distance between the wells. Reliance on a formation analogue or to the one provided by a comparable well documented reservoir, is essential to acquire this parameter. The closer the analogue by its age, environment, in a similar situation in terms of sequence stratigraphy at the

given order (3, 4, 5 and beyond) which concerns the heterogeneities to be characterized and in the same context of the evolution of the orders, the better the result.

The horizontal variograms were calculated in the Long Nab cliff on a whole series of lines at 30 cm intervals. The minimum calculation step of each variogram was 1 m. This calculation accuracy was then applied to many sites representative of various environments, in order to extract more general rules and to compile a reliable database. In the Long Nab cliff, the evolution of the characters of the variograms helped to identify families of variograms characteristic of different units *(Fig. 9)*. Some had been observed in the field. Others had not been initially discerned on the outcrop and incited a search for the causes of these families. A larger scale study showed that they were different units but displayed very similar characteristics in the zone analyzed. Another general result was to demonstrate a dominant exponential type of variogram, which permitted the development of an efficient simulation method via calculation.

The simulations do not use the individual variograms. These serve to analyze the spatial behavior of the units investigated and to differentiate between the units. This step is decisive for the rest of the calculation. It corresponds to the "structural analysis" of the geostatisticians (another source of confusion in discussions with the researchers of this discipline, yet another being the origin 0° of their calculations which corresponds to the trigonometric origin but not to the reference north of the geologists, hence the lengthy discussions on the 90° offsets encountered at the beginning of the collaboration!). It was then necessary to group the variograms of the same family (it is important to distinguish each family because each is representative of elements with very similar spatial properties which can be modeled in the same unit) to obtain one or more average variograms (*Fig. 9*). The number of these variograms obviously depends on the initial data, and the problem to be solved (the precise definition of the problem to be solved is often difficult, and the future users of the simulation results often have trouble in formulating it, or refuse to formulate it

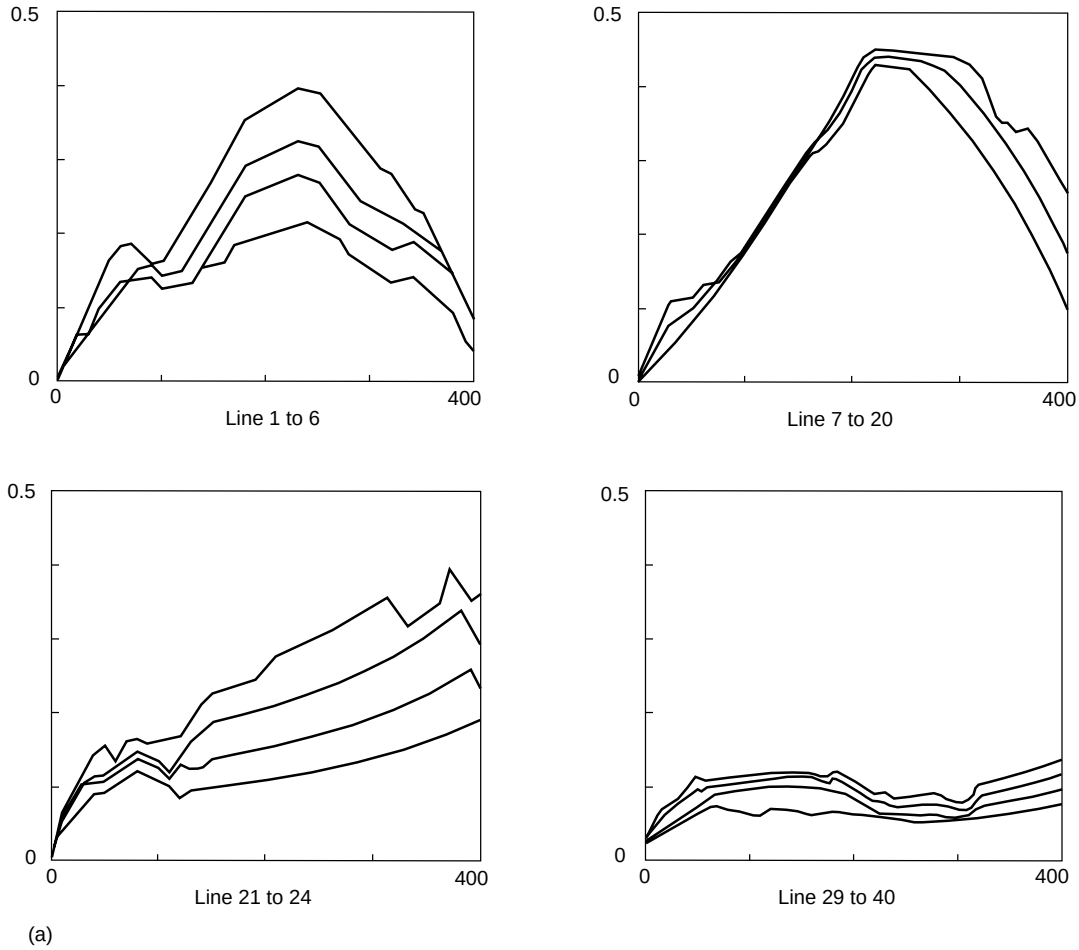

Figure 9a

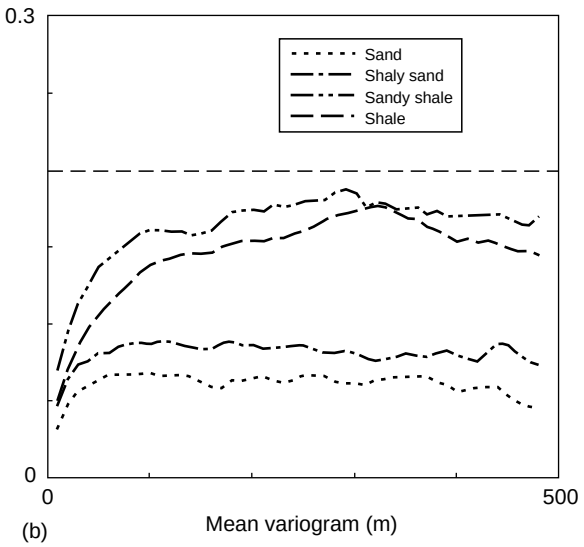

Figure 9

Family of variograms calculated along lines parallel to the datum level and average variograms for different lithologies (Ravenne *et al.*, 1990).

The four first figures (p. 320) show a progressive evolution of the individual variograms calculated line by line (at 30 cm intervals) in prism I of the Long Nab site. This evolution displays breaks which helped to distinguish four families corresponding to variations in the arrangement of the strata within the prism. The lower figure (this page) emphasizes the relationship of the sands and argillaceous sands to the clays and sandy clays.

for vague reasons of confidentiality; yet the examination of the data, the search for datum levels, etc., differ according to the accuracy desired). The larger the number the greater the need to calculate different simulations. These average variograms are not used as such but adjusted to one or more models from which the parameters mentioned previously (range, type, sill, behavior at origin) can be easily extracted to make the simulations. The first simulations made on this site used vertical ranges of 10 m, horizontal of 175 m in the north-south direction and 350 m in the east-west direction.

Implementation of the Simulation Method

This method was developed by Matheron *et al.* (1987, 1988), the creator of geostatistic science. He participated continually in its most rigorous developments. The method was developed to answer the problem of heterogeneities and facies variations controlled by the stratigraphic context and not like other methods created in the "absolute" and which were tentatively applied to natural environments. This was only possible because of a real multidisciplinarity and an effort at mutual understanding of the needs, the work and the possibilities (state of knowledge, ongoing problems) at the given time of each discipline.

The method is based on the simulation conditioned by well data of Gaussian variables. The value of the facies is then determined from the value of the gaussian according to its position in relation to the thresholds supplied by the vertical proportion curve: if *Y(x)* is the value of the Gaussian at a point *x* and if *Y(x)* is lower than the threshold of facies *A*, point *x* is attributed to facies *A*. This method proved to be promising, its results were validated on many real cases, and methodology and method culminated in the industrialization and marketing of the Heresim (Heterogeneities, REservoir SIMulation) software. The Greek word hairesis means choice and this name recalls that a choice must be made between several types of simulation (Fouquet *et al.*, 1989; Galli *et al.*, 1990; Doligez *et al.*, 1992a, 1992b; Chautru *et al.*, 1993; Galli and Ravenne, 1995). Its development in the course of this study implied numerous simplifying hypotheses such as planeity and parallelism of the units which limited its immediate application to more complicated cases. However, as such, it corresponded to a major breakthrough and helped to advance far beyond what existed at the time. The situation described is the one that prevailed in 1989 and since then, constant efforts have been focused on developing methodologies, methods, incorporating situations and increasingly complex cases: horizontal nonstationary, complex envelopes, nesting simulations, differential subsidence, faults (Beucher *et al.*, 1997, 1999; Doligez *et al.*, 1999a).

The result of the simulation is a 3D volume consisting of pixels which is qualified as high resolution in relation to the low resolution volume that is used for the fluid-flow simulations by the reservoir engineer. The mesh height is generally 30 cm, or even 50 cm or 1 m to be compatible with the resolution power of the logging tools (in fact, few boreholes are cored continuously and the only information really available is that provided by the logs), and its width varies from a few meters to several tens of meters. Each mesh is assigned a value corresponding to a lithofacies.

The choice and number of lithofacies always depends on the problem to be solved and the available information. Since the number of wells increases during the production of a field, the number of data increases and the problems to be solved concern increasingly restricted zones. It is therefore very important from the outset to describe all the wells with maximum accuracy in order to avoid subsequently recreating the whole database (if this is still possible, because many data have been lost or subsequently deteriorated). It is also important to distinguish what is certain from what is possible, particularly for the envelope or correlation surfaces in order to test the different possibilities and make the wisest possible choice.

Some facies can be judged to be minor basically and yet they may prove to be decisive as a permeability barrier or a datum surface for correlations and calculations. Thus in the case process for the control of the model, levels of very fine calcretes (a few centimeters thick) were the key to decipher

the complexity of the reservoir. These levels are not considered for their reservoir or caprock properties and were therefore ignored. The conceptual model of the reservoir was very simple and consisted of a stack of channels disposed in parallel strata *(Fig. 10 right)*. The study of an analogue with really comparable characteristics with those of the reservoir helps to demonstrate the importance of these calcrete deposits as paleohorizontal indicators at the scale of this reservoir. The precise consideration of these levels in the field led to the survey of three tectonic episodes and a major erosional phase in "the" reservoir concerned *(Fig. 10 left)*. The channels were far from arranged in parallelplanes, the conceptual model was highly reductive and all the previous calculations were meaningless because pertaining to different units (transition through a discontinuity) or they had been made parallel to the paleohorizontals. The simulations made with the new subdivision finally helped to explain and understand the dynamic behavior of the field, which hitherto posed very serious problems to its operator.

The use of a large number of facies allows an easier qualitative check by the geologist who can immediately distinguish the inconsistencies with the conceptual model and validate or disprove the results obtained. Complementary facies can be created to take account:

– of diagenetic variations (knowing that in most cases the diagenesis at the scale of a field is closely controlled by the stratigraphic context;
– of variations in petrophysical properties or
– to take account of variations within a sedimentary body, as for example, in the case of meandering channels with levee-facies, filling bases, accretion bars.

Once this check has been completed, the number of facies for the simulation useable by the reservoir engineer can be reduced to meet the objectives of the simulation in each given case. Here also, this reduction of facies which limits the geological input is done in close collaboration with the other disciplines involved.

A simulation is merely a simulation. It is not the reality. It is one possible materialization of the reality which, with the method employed, already substantially reduces the uncertainties, especially if the range parameter has been correctly calculated. The percentages of lithofacies are generally well known if a dozen wells or randomly distributed sections are available. The best selection among the different products is the one for which the results of the dynamic simulation agree with the actual production data. However, one cannot dynamically test all the results, since at the time, and still today, computer times were extremely long. As a rule, ten results are calculated with identical parameters but with seeds of initialization of the different simulations. One and only one dominant trend generally emerges, sometimes two results differ significantly about a mean calculated for all the simulations. This mean cannot be used for dynamic simulations because it corresponds to an

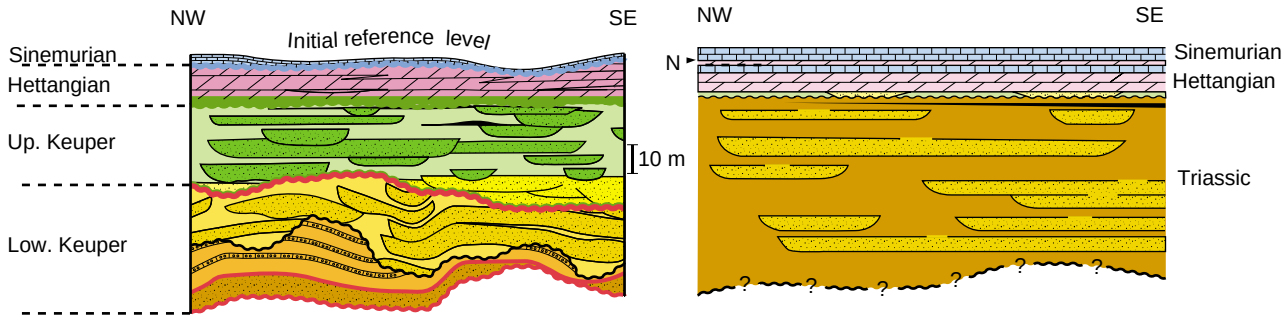

Figure 10

Comparison of two reservoir schemes obtained before and after consideration of the calcrete level as a datum level (Houel *et al.*, 1991).

The right hand figure corresponds to the reservoir image used by the company to construct the flow simulation models. The datum level used for the calculations was the base of the Sinemurian. All the wells (about 35) were cored continuously and produced a highly complete set of logs. The analysis and sedimentological description had been extremely thorough. The problem which soon emerged was the inability to fit the model to the operating results and dynamic simulations. The right hand figure was made possible by the consideration of calcrete levels (about some cm) as correlation levels. These very fine levels had been clearly been observed, but having no reservoir related property, had been ignored. Their importance was demonstrated in the study of the Almedina site which had been selected as an analogue for the study of this field. A comparison of the two figures reveals the meaninglessness of the calculations made in parallel and perpendicular to the initial datum level, because in reality (left hand figure) these calculations concerned stratigraphically different series and could even intersect unconformities, whereas they must be made in a precise stratigraphic context.

estimation (close to a kriging). The estimation enormously smoothes the heterogeneities which are the main subject of concern for these dynamic calculations, while the "static" simulations take account of this variability. Hence the choice falls on a simulation that satisfies the main features of the mean but which remains a simulation.

Conversion of Lithofacies and Change of Scale

The simulation results thus obtained are not always useable by the reservoir engineer, although many geological parameters (facies, envelopes) are now supplied in the form of grids of numbers. On the one hand, the lithofacies are not useable as such, and on the other, the simulated volumes contain too many meshes, often more than one million, sometimes several tens of millions or even hundred of millions.

The first conversion consists in replacing the lithofacies by petrophysical values: porosity and permeability. Other properties were subsequently added. The basic assumptions that led us to simulate the lithofacies first were that the heterogeneities were closely related to the stratigraphy, and that the petrophysical properties were associated with the lithofacies with values strongly dependent on the link between lithofacies and their place in the tract in sequence stratigraphy. As stated earlier, the diagenetic modifications are thus dominated by this link. In fact, in a given lithofacies and in a sequence of the 5th or 6th order (Vail *et al.*, 1991), the petrophysical properties vary by less than one order of magnitude, and the attribution of the physical properties can be made freely either by attributing a fixed value per lithofacies in a given unit, or by a Monte Carlo sorting in the range of values found within the lithofacies, or even by one or the different types of kriging.

Subsequently, it was and still is necessary to reduce the number of meshes to be compatible with the current computation possibilities by trying to preserve the dynamic properties. This step represents what reservoir engineers call "homogenization" and which is always the subject of intensive research. This aspect was mainly developed by Guérillot *et al.*, (1989, 1990a, 1990b, 1991). The formula used was tested on a block of Yorkshire sandstone (Jacquin *et al.*, 1991) which still leaves the author with the memory of his climb from the bottom of the cliff to the summit. This block was then cut into a parallelepiped 90 cm long with 30 cm sides. The overall permeability was measured. The block was then cut into three equal blocks of which the overall permeability was also measured. Finally, each of these blocks was cut into a larger number of "plugs" (very small cores measuring about one inch in diameter and a few centimeters in length) of which the permeability was also measured. The formula was applied by using the grid consisting of the permeabilities supplied by each "plug" and the result compared with the permeabilities of the large block and each of the three sub-blocks. The comparison was deemed sufficiently satisfactory for the formula to be applied in the Heresim software. Today, this formula is still proposed in the software and others have been added to address more complex situations.

Controls of the Model: Yorkshire, Ravenscar Site and Underground Storage

A first control was performed on the Ravenscar site (Yorkshire). The simulation made on the Long Nab site only concerned one Formation and was hence relatively simple. The application of the method to the Ravenscar site was already more complex because several Formations deposited in very different environments were present and sometimes separated by discontinuities. The reconnaissance of the

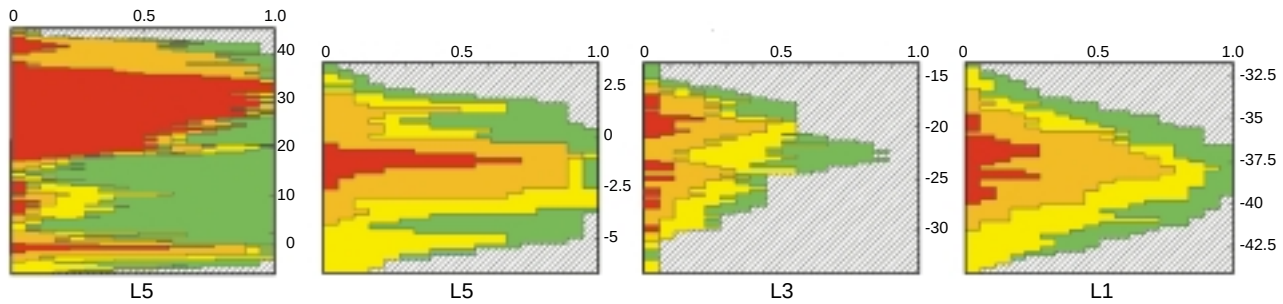

Figure 11

Proportion curves calculated with poor and good datum level (Doligez *et al.*, 1992a).

The left hand curve shows the proportion curve calculated on the entire Ellerbeck Formation (Ravenscar site). The lithofacies range from clean sandstones (red) to clay (green). A large proportion of clean sandstone is observed between 18 and 36 m, which means that nearly all the wells crossed this bar. Such a bar will have a very clear log signature and, depending on the correlation assumptions made, the correlation levels will be located preferably at the top or the wall of the bar. Such correlations culminate for the portion between 0 and –5 m in proportion curves denoted L3 and L1, where no organization is visible and where the percentage of clean sandstones does not exceed 25%. The good datum level corresponds to the maximum flooding surface (level 0 in the left hand figure) and leads to the proportion curve L5 where the clean sandstones reach 70%. The impact on the simulations is shown in the next figure.

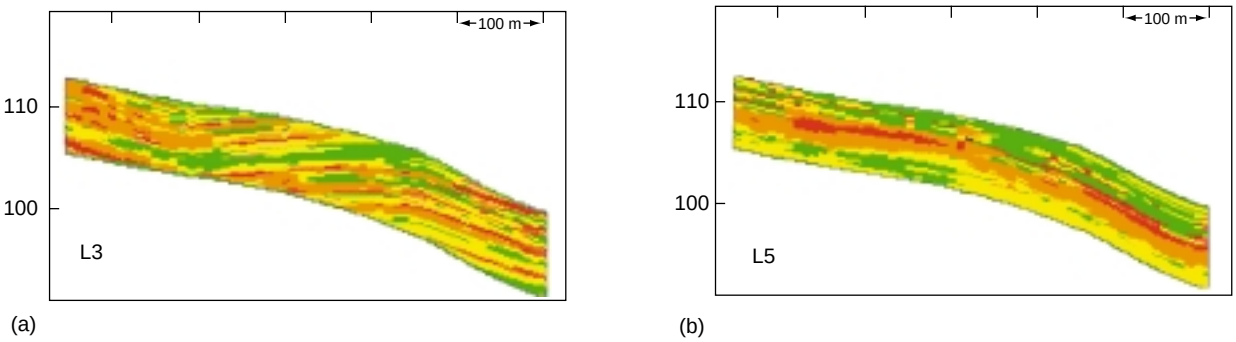

Figure 12

The two simulations obtained from the proportion curves of the previous figure (Doligez *et al.*, 1992a).

The simulation obtained with datum level L3 only shows very few horizons rich in clean sandstones (reflecting the maximum proportion observed level by level, Fig. 11) and moreover, these sandstone rich portions are very discontinuous. The simulation obtained with the good datum level L5 reveals a very continuous horizon, rich in clean sandstones, which represents a potential reservoir of interest both for its oil and gas resources and for aquifer management.

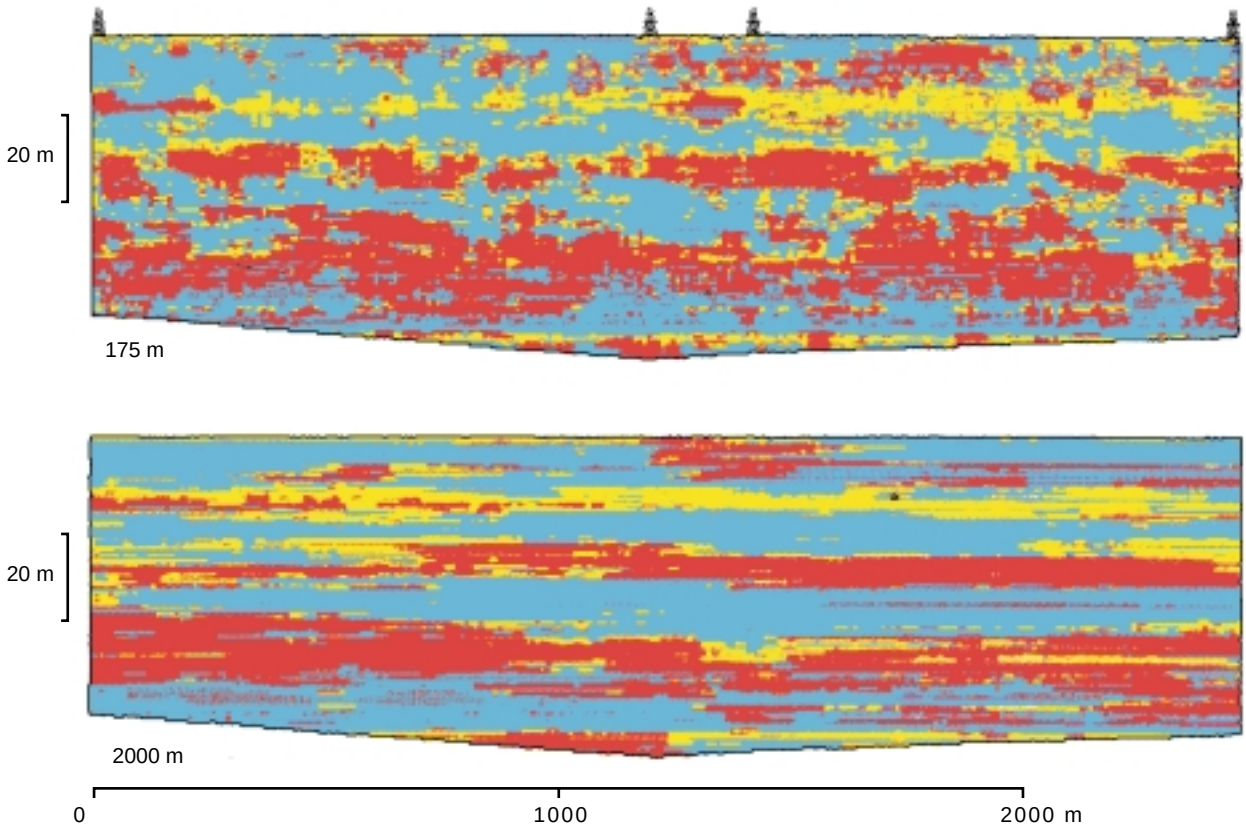

Figure 13

Simulations in lithologies with a large range and a small range (Ravenne *et al.*, 1990).

The same vertical proportion curve was used in both simulations, and only the range of the variogram was changed. The Gaz de France reservoir engineers and geologists all preferred a bottom simulation made with a range of 2000 m (the good reservoirs are in red, the caprocks in blue), which emphasized the stratigraphy, but above all, which had the same shape as the "layer-cake" models; the dynamic results obtained with this model were unsatisfactory. Good results were obtained with the top simulation (range 175 m calculated with the entire Almedina database, another advantage of such databases because the well spacing is not sufficient to obtain the horizontalrange). The very noisy appearance is mainly due to the differences between the vertical and horizontal scale. These simulations were the first to be performed for an industrial purpose (already carried out in 3D, but without a proper means of 3D visualization at the time: 1988). The result of the progress achieved in the methods and the visualization are discussed below (Figs. 16 to 21).

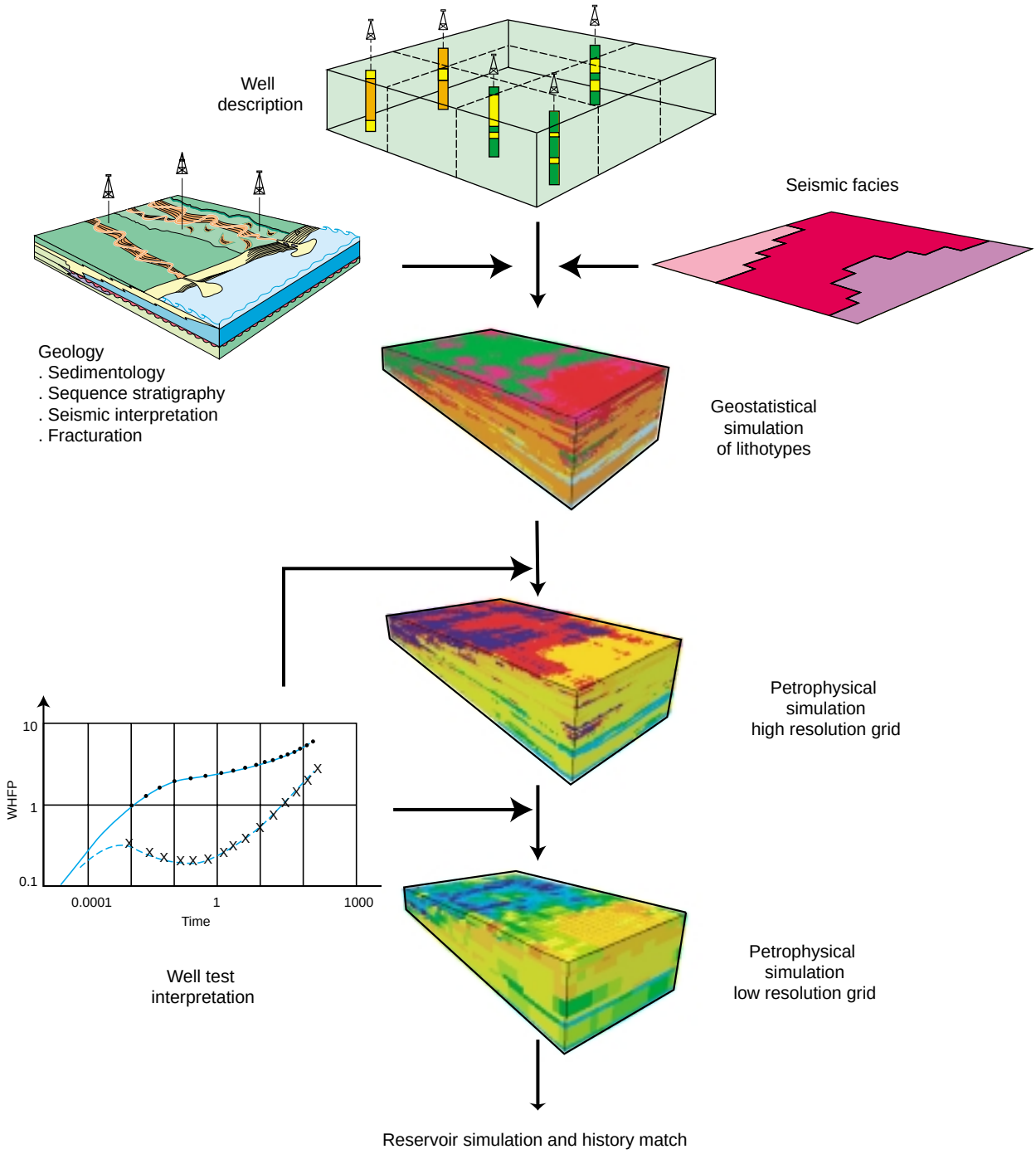

Figure 14

Simulation of reservoirs: sequencing of steps (Doligez *et al.*, 1999a).

The two preliminary and fundamental steps are the description of the wells and the detailed geological survey. The seismic study is then incorporated to make the geostatistical simulation of the lithotypes with a very high resolution (mesh routinely 30 cm vertical and 1 to 5 m horizontal); these simulations contain up to 10 M meshes, which is incompatible with the power of the present fluid-flow simulators. The lithotype grid is then completed with the petrophysical properties (porosity and permeability), again with the same number of meshes, and a change of scale is then applied to have a grid compatible with the powers of the fluid-flow simulators. The results then obtained are compared with thehistory matches. These comparisons are highly positive insofar as the sedimentological and sequence stratigraphic study has been carried out correctly and there is no need to make multiple adjustments.

discontinuities appeared to be crucial and the simulations made demonstrate the importance of choosing the datum levels for the calculations and the results obtained. Thus for example, a correlation level located at the base of a sand sheet, or at least which appeared to be at the scale of the site, was tested. This was justified by the fact that a "conventional" study at the time, not in sequence stratigraphy, would have led to the choice of this marker by lithostratigraphic correlation. The first result was a very noisy vertical proportion curve (*Fig. 11*, reference L3) leading to the second result: a simulation with very discontinuous lithofacies culminating in a negative conclusion as to the potential interest of such a reservoir (*Fig. 12*, reference L3).

The simulation made using the major flooding surface as the datum level, very discrete on the logs, reveals on the contrary, an excellent reservoir level (*Fig. 12b*), both for its petrophysical properties and its lateral extension. The final result of the simulations was very positive and encouraged an attempt at validation on a real reservoir.

The second control and validation of the study methodology for geological data and of the simulation method, were carried out on data found in underground storage facilities by *Gaz de France.*

This validation has already been discussed in the section on the development of the simulation method concerning the importance of the calcrete levels as markers of deposition paleohorizontals which could serve as a reference for the calculations. All the studies performed for the validation are not recalled here, but one point concerning the visual appearance of the simulations will be emphasized. Given the well spacing, it was not possible to calculate theranges. Various ranges were tested, and it was found that the one most popular with the reservoir engineers was the one that increased the continuity of the lithofacies because this fairly accurately reproduced the shape encountered in the "layer-cake" models frequently used. After the studies of an analogue and dynamic simulations, it turned out that the good value of the range was much smaller, leading to very discontinuous images, that did not please the users at the time (*Fig. 13*). Some reluctance is still encountered today.

Finally, the results were deemed sufficiently positive for the methodology (*Fig. 14*) and the model to be validated, and it was decided to pursue research and development on the topic of reservoir characterization followed by the industrialization and marketing of the software.

1.4 Other Studies Conducted

Only the final section is illustrated to show the progress achieved.

The other sites investigated were mainly aimed to improve the sequence stratigraphic knowledge and the development of the database for the various types of geostatistical modeling. Only the most important of them, which illustrate the problems encountered and the development of the methodology, are mentioned here, without going into details of the results obtained, because these studies were carried out as part of projects involving several partners, and for which an obligation of confidentiality still prevails.

1.4.1 Yorkshire 3 (United kingdom; 1989-1990)

This site, located to the south of the first one, was investigated at the request of French oil companies. This study was aimed to check the variability of the geostatistical parameters calculated on sedimentary bodies deposited in similar environments and the application of the exponential adjustment model for the variographic calculation of such environments. This site corresponds to the same valley fill as that of Long Nab *(Fig. 4)*. It differs from it by the presence of two meandering belts in the median prism (a single one at Long Nab) and by a more pronounced heterogeneity. The important point is that the same families of variograms, the same rangesand the same type were identified. These results were therefore conclusive and demonstrated:

– that the geostatistical parameters certainly permitted a quantification of the sedimentological data, and that they could provide help for the qualitative interpretation of these data;
– that the exponential adjustment model could be applied, ensuring a significant gain in time in the subsequent calculations.

1.4.2 Roda (1990-1993), Cajigar (1990-1993), Poulseur (1990-1993)

These sites, examined in connection with the Joule (EU) Program *(Geosciences JOUF* 00-34 project) conducted jointly between *EEP (ELF Exploration Production), PETROFINA* and *AGIP* (managers H. Soudet then O. Dubrule), were aimed to calibrate the probabilistic presentations of the reservoir heterogeneities with current analogues. In all these sites, *IFP* and the *Centre de géostatistiques* acted as subcontractors, whose initial mission was to carry out the calculations and geostatistical modelings and to implement the acquisition method developed in connection with the previous site (hence, interalia, to guarantee the effective multidisciplinarity and to provide liaison/communication with the geostatisticians. The role was nonetheless more important and these sites served to validate the acquisition and quantification methods on a wide variety of sites, and to check the power of the proportion curves tool in widely varied environments: delta (Eocene, Roda, Spain), shallow platform carbonates (Frasnian and Framenian, Poulseur, Belgium), very proximal and lacustrine alluvial deposits (Eocene, Cajigar, Spain).

In the Roda site (Eocene of the Spanish Pyrenees, 1990-1993) it was demonstrated (Lesueur *et al.*, 1994) that the

fluvio-deltaic system of the Roda sandstones was deposited during a 3rd order cycle comprising several 4th order sequences. Three of these sequences were modeled; each of them was controlled by high frequency variations in relative sea level, and consisted of alternating sands deposited during periods of regression and marls or marley limestones deposited during periods of transgression which formed permeability barriers. Other barriers (cemented levels) are due to autocyclic processes. Joseph was the sedimentologist most involved for the purpose of modeling of the project (Joseph and Dubrule, 1994) and when was with Hu (Hu *et al.*, 1992) of the *Centre de géostatistiques*, the creator of a new simulation method: random genetic modelings (the thresholded Gaussian method did not make it possible at the time to take account simultaneously of the complex deposition geometries with wide variations in dip). This method served to test several setting hypotheses of specific deltas with a high input rate and characterized by a steep dip. This highly effective method was not industrialized because too costly for its development in comparison with its application, that was limited to rare deltaic systems or not recognized as reservoirs.

The Poulseur site (Belgium, Upper Famennian) could not be analyzed on its entire area because many species of birds of prey nested there. Numerous highly detailed sections were surveyed in the cliff every 2-3 m and over a total authorized length of less than 60 m. The largest cautions were expressed concerning the results that could be obtained. The surprise was to be able to demonstrate clearly a whole history rich in relative variations in sea level, hence a succession of sequences (eleven 4th order, Préat and Mennig, 1994), particularly to reveal the vertical evolution of one of these sequences (Ravenne *et al.*, 1994), and also to indicate the lateral polarity of the deposits with the horizontal proportion curves. This result was obviously obtained thanks to the quality of the data acquired, but which could not be interpreted so directly. The statistical analysis immediately helps to identify the evolutionary trends of a sedimentary series by knowing the inherent specificities of each section.

The Cajigar site (Spain, Upper Eocene-Lower Oligocene) was very closely investigated by researchers (Fonnesu *et al.*, 1994) participating in the project and trained by professor Mutti. The work was evidently of excellent quality for the analysis and understanding of the sedimentary series. Efforts were mainly focused on the central unit CJ2 (three units were surveyed) of which the environment varies from an alluvial to lacustrine cone. Six deposition sequences (CJ2a to f) were distinguished. The complexity is such that the two sequences (CJ2 c and d) subjected to later calculations were subdivided into seven litho and chronostratigraphic subunits. However, as part of the attributions of the author to conduct the rest of the geostatistical study and then the modelings, a request was made that complementary sections be surveyed to obtain significant statistical results and hence obtain significant proportion curves. In fact, the sections have been surveyed at key locations to decipher the sedimentary logics, but these locations, not randomly distributed, were not suitable for estimating the volume of a particular type of sandstone or of conglomerate at a specific level. This point is important for the application of quantitative geology. This was clearly demonstrated in the study (Doligez *et al.*, 1994), because only the totality of the sections served to obtain proportion curves reflecting the evolution of the facies.

1.4.3 Almedina (Spain, 1990-1992)

This site was already mentioned in the study of the first site, because it represented the analogue for the application (and validation) of the methodology and of the simulation method for the *Gaz de France* underground storage facility (Mathieu *et al.*, 1993). It is located in the Trias of La Mancha in Spain, and displays sediments deposited in fluvial to lacustrine environments.

This site enabled the finalization by Désaubliaux (Houel *et al.*, 1991) of the development of the quantification method by pseudo-wells for 3D geological analyses performed in the cliffs. 3D because for the variographic calculations and particularly for the behavior at the origin of variogram and the search for anisotropy directions, it is important to know the exact position of each measure point. A cliff is rarely vertical and rectilinear: it displays curves and scarps and ledges which must be considered, especially if the results obtained are to participate in developing a database. The method first brought forth photographic pictures, followed by topographic measurements which then allowed 3D restoration of the image of the cliff. This image was then completed with facies and petrophysical properties by using the results of surveys of several vertical sections in the cliff. These tasks completed, it was then possible to construct the pseudo-wells for each vertical and accurately located section. The points recorded in the ledges were projected on intermediate sections.

Since the aim was to explore and make the most detailed possible use of the proportion curves and variograms, the work done was exhaustive: a pseudo-well was located every 10 m on about 15 km of cliff and on a height of about 30 m.

This site also permitted:

- The finalization of the pseudo-well method.
- The clear differentiation by the proportion curves of meandering channel systems according to whether they were deposited in a period of high rate of creation of available space, or in a period of low rate: the deposits associated with meandering channels in a high accommodation rate period of the creation of available space are marked on the vertical proportion curves by a fairly symmetrical bell shape and a regular evolution of the facies, both in the rising portion and the descending portion *(Fig. 7)*. In a low rate period, these curves are

asymmetrical, with, immediately at the base, the maximum concentration of the most coarse-grained facies followed by their progressive decrease in favor of channel abandonment clays (clay-plugs). These features can be considered as general since they were often found in very different sits. These very particular signatures, in light of the proportion curve, serve to describe a part of the history of the deposits without having other information than the petrographic construction and the particle size distribution. This forecast was carried out in particular in the study in a real reservoir made jointly with *AGIP*. Stress must be placed here on the power of this software for sedimentological and stratigraphic studies, since the statistical aspect helps to identify the evolutionary trends which only appear with much greater difficulty on the individual sections, and at the cost of substantially greater work. I have already mentioned the other advantages of these curves earlier.

– The obtaining of the differentiation key between fluvial plain and channel abandonment clays on the logs. This result was achieved by Matthieu (Houel *et al.*, 1991) using processed dipmeter data. This point is important because if the two types are not distinguished, the resulting images of the reservoir geometry are very different from reality. without distinguishing between them, the trend will be correlate the wells between one another at the first appearance of clay. The result would be a reservoir image constituting a very continuous sand sheet at the top and a succession of channeled bodies at the base, which would not shock the interpreter. In this context of a low creation rate, the reality is a very continuous sand layer at the base, which is highly subdivided at the top by abandonments of meander arms filled by these clays. This result is far more surprising to the interpreter, and this correlation scheme cannot be applied spontaneously if the differentiation key is unknown. It is easy to understand why these two representations lead to very different fluid production and flow schemes. These conclusions were validated by several field studies and by the application with simulations to the actual case investigated with *AGIP*.

1.4.4 Mesaverde (United States, 1991-1993)

The outcrops of the Mesaverde (Colorado, Upper Cretaceous) are silicoclastic sediments deposited in shallow coastal and continental marine environments, appropriate for the studies conducted at *IFP*, their quality and continuity offering the possibility of 3D studies because the cliffs are notched by numerous canyons. The studies continued for several years (1991 to 1993) with Wright-Dunbar (1986) who had recently finalized a synthesis on these series. This study helped to establish a genetic and geometric model of the distribution of the sedimentary bodies in a second order regressive-transgressive cycle 2 (10 Ma) that was then applied successfully to the Brent group in the Tampen Spur zone (North Sea). It was demonstrated that the reconnaissance of the gullying surfaces (which form in a period of rising sea level and are hence diachronous, not to be confused, representing the difficulty, with the erosioned surfaces generated in the decreasing sea level period) represented the essential factor for deciphering the history of said cycles. This is particularly difficult since the deposits which accompany these surfaces are often very reduced. Finally, this study helped to obtain details for establishing correlations between marine and continental deposits, particularly for the definition of the accommodation rates: the rise in sea level causes a rise in the base level that allows the deposition and preservation of the coastal and continental sediments (often with isolated channels), while the lowering of the sea level causes a fall in the base level that generally does not allow deposits in a continental domain. The results and the databank obtained tend to constrain the deterministic modelings.

Deterministic modeling serves to take account of successions of sequences with paleobathymetry constraints. The Dionisos software designed by Granjeon, (Granjeon, 1997; Granjeon and Joseph, 1999) can be used to test various hypotheses, and is a correlation tool of shorter duration sequences than those identified and correlated by the geologist and supplies wide facies variations. It is used before the stochastic simulations because it takes account of the most reliable knowledge (deterministic aspect) in each case investigated and provides the additional constraint for the nonstationary simulations with facies variations. Since it can be used on very large volumes, it is also an excellent tool providing the transition with the basin modelings (see Lerche, 1989 and Lawrence *et al.*, 1990).

These projects:

– supplied keys for correlations between marine and continental domains, particularly with answers to the variations in creation of available space in a large second order regressive-transgressive cycle (roughly lasting about 10 Ma);
– served to clearly demonstrate the evolution of the geometries of sedimentary bodies deposited in similar environments but in different sequence stratigraphy contexts. These outcrops represent a remarkable analogue for numerous North Sea reservoirs and any reservoir study, even if it concerns sedimentary bodies deposited in very short periods, must integrate a wider context to replace the sequence examined in its evolutionary cycle.

1.4.5 Return to the Annot Sandstones (France, 1995-2002)

Ten years after the work done on the Annot sandstones to supply an aid to seismic interpretation, a new study on these sandstones was resumed, this time with the aim of understanding the reservoirs. It was done with a consortium proposed and led by Joseph, since 1995, to better characterize and understand the heterogeneities of submarine deposits of gravity origin.

The successes registered in the exploration of deep submarine deposits by numerous oil companies—particularly the pioneering role of *PETROBRAS*—led to the resumption of studies on analogues. These are rare. The Annot sandstones do not represent the ideal analogue for many oil and gas reservoirs located in series deposited in a stable margin (or passive, or in extension) setting, because they were deposited in a foreland setting (in a roughly in compression domain) but the depositional processes are probably the same, and the heterogeneities and grain size distributions closely comparable to those of many deep submarine deposits.

The resumption of the study of the Annot sandstones was initially aimed to investigate a reservoir offshore Brazil. Previous studies conducted at *IFP* supplied the proprietary framework for the development of this study. Many processes had already been understood following analogue modelings of turbid surges carried out with Beghin (Ravenne and Beghin, 1983). The final objective was clearly innovative, and so were the approach methods. Some of the main results can be found in the guidebook of the *AAPG* excursion of Nice (Ravenne *et al.*, 1995b).

The crucial problems that subsist are the lack of criteria allowing a grasp of the bathymetries insofar as the water depth becomes higher than a few tens of meters, and, despite the number of studies on the "turbidites", the lack of knowledge of this type of deposit. The resolution of these problems entails the development of synergies between the different earth science disciplines. What is unfortunate here is the lack of a drilling ship dedicated to the rigorous and detailed exploration of recent sedimentary series of which the depositional environment is undeniable. By itself, this would allow the acquisition of the data necessary to calibrate the seismic reflection and side scan radar data.

1.4.6 Algeria, Tunisia (1995-1998)

In 1995, a consortium of *SONATRACH* and *IFP* was asked to make a synthesis of the Algerian Triassic from outcrop data and a large body of well data (cores and logs). The synthesis work of Busson (1970, 1972) and of Boudjéma (1987) did not take account of the many wells owned by *SONATRACH*.

The EasyTrace software (Fournier, 1997, 1998) adjusts and calibrates the seismic wavelets used particularly for the inversion calculations. It uses specific logs and above all, those of the density and "sonic" measurements, *i.e.* the log recording the *P* wave velocities in the immediate neighborhood of the well. This tool provided a safe and reliable basis for the introduction of seismic constraints in the geostatistical simulations, because the same dimensions were used for the same markers and the different layers; the use of other logs helped to achieve a better definition of the lithofacies. The development of this tool allows the automatic compilation of a numerical database necessary for all the calculations prior to the simulation and for the simulations themselves.

Montadert, in the late 1960s, had obtained sections in the Triassic of the Zarzaitine cliff (Groult, 1970). These sections were not surveyed with the principles used today. However, the quality of the observations makes them highly usable. The additional work needed consisted in replacing these descriptions in the ideal format. This point is important, because university and industrial archives often contain data of very remarkable quality, which can and should be used, particularly since the time spent in their acquisition was often more generous than today.

During this study, 127 wells were investigated and over 7 000 m of cores were described at 1:100. The author was the first (and only) Frenchman to return to Hassi Messaoud at that time (July 1995) to participate in—and lead—the description of the cores, in summer and in an open space where shade disappeared quickly! Many field sections were surveyed in Tunisia (1996) and Algeria (1996, 1997). All the available logs were digitized to calculate the electrofacies with EasyTrace in order to make up for the lack of petrographic and sedimentological knowledge of the uncored intervals. Among the main results (Eschard *et al.*, 1998a): the correlation between the different basins of the Saharan platform and the reconstruction of the depositional systems at regional scale. The fluvial regimes were controlled by the arid or semi-desert conditions which prevailed within the Upper Triassic. The depositional systems included:

- endorheic basins in which the distal portions of the fluvial systems (often marked by ephemeral anastomosed channels) were interdigited with ephemeral lakes and flood plain deposits;
- wide braided fluvial systems occupied large portions of the basins;
- sabkha environments. The lithographic formations are strongly diachronous. A revision proposed of the palynological scale deported by precise samplings helped to establish a stratigraphy offering a new framework for regional scale correlations.

Thus a general "onlap" was identified of the series towards the south and a retrogradation of the depositional systems. A major task still remains to be accomplished, because certain basins are only crossed by rare widely spaced boreholes, not allowing precise correlations.

1.4.7 Other Sites

The sites previously mentioned are those in which the author was directly involved either for sedimentological analyses, or for quantification aspects. During his direction of the team, other sites addressed the following environments: mixed silico-clastic/carbonates in the Paradox basin in the United States (1993-1995; Homewood and Eberli, 2000), carbonate

(reefs) in Alberta, Canada (1993-1995; Homewood and Eberli, 2000) and in Italy (1994-1995; Stefani and Van Buchem, 1997), eolian in Colorado (1995-1997; Eschard *et al.*, 1997), etc. On every occasion, the analysis of these outcrops continued to advance the knowledge in sedimentology and sequence stratigraphy and to supply the databases for the proper use of the various simulation methods.

1.5 Work Completed: Application to Real Reservoirs

Only the information which helped to improve the methodology and/or simulation methods is given here, because these applications were usually carried out in connection with contracts including severe confidentialarity requirements. In some cases, specific points are mentioned for their ability to illustrate the approach followed, in order to solve the problems, and to expand the knowledge available.

1.5.1 El Borma

This site was the second main site investigated in the reservoir characterization project. This was done as part of a new Thermie project (1991-1994, European Union) conducted jointly with *AGIP* and *ARMINES*. Its aim was the industrialization of the Heresim software, its validation on a real reservoir, and the demonstration of its use by an industrial partner. It also offered the opportunity to add many supplements and to improve the user-friendliness of this software.

A reliable and large data bank was available for this study, and its compilation already took account of high resolution sequence stratigraphy concepts. However, every data bank—and this was confirmed in each real case study—contains residual errors. The partners of AGIP, Rossini and Volpi, had participated in the synthesis of this reservoir and assessed the power of the statistical and geostatistical of the Heresim software.

This study was widely disseminated with *AGIP* (1994). It allowed a considerable gain in the time needed to pose and solve the problems pertaining to a reservoir. In addition, many assumptions were tested. New results were obtained:

– definition of new reliable markers;
– identification of discontinuities, displacement of deposition centers, stacking of complex channel fill phases associated with variations in the creation of accommodation space.

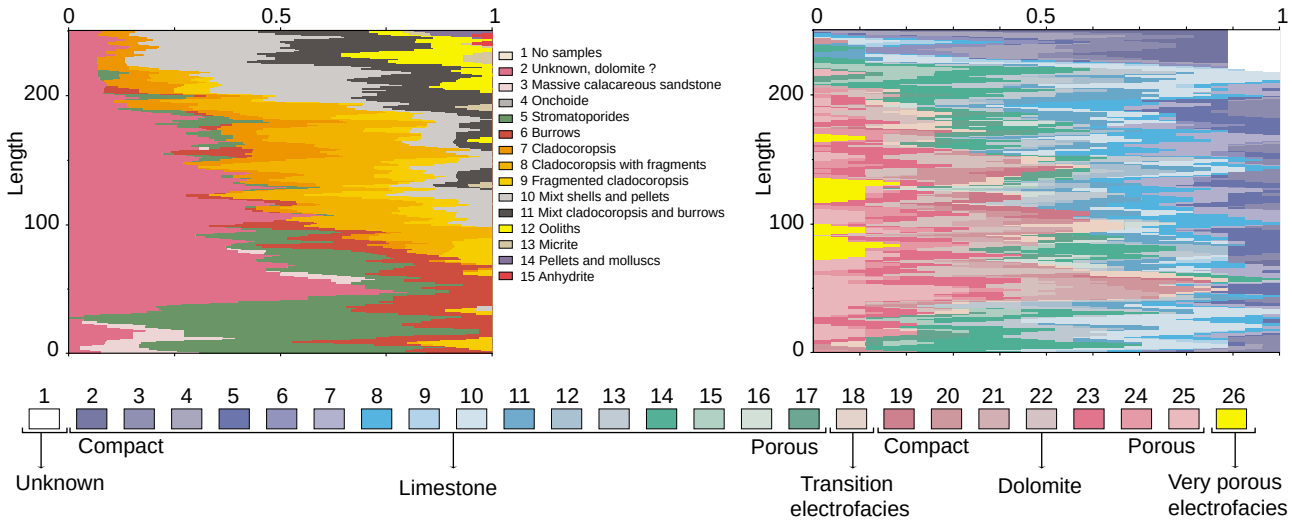

Figure 15

Proportion curves obtained from: 1: core data, 2: electrofacies.

The sector investigated has more than 150 wells. Only nine were cored continuously in the considered interval. The left figure shows the vertical proportion curve obtained with the lithofacies. These nine wells were insufficient to constrain the simulations required on the overall sector (25 × 25 km). It was therefore necessary to use the available logs ins the other wells and determine the electrofacies. The challenge was severe one because the tools and techniques had never been employed in such series. The result was conclusive: the right hand figure shows the proportion curve calculated with fifteen randomly distributed wells over the entire sector. The similarity is remarkable, particularly in the evolution of the forms and peak to peak. The timescale covered is less than 1 Ma. The two figures show that the major sequence, underscored by the steady decrease in dolomite from the bottom upward, can be divided into six genetic units with an approximate duration of less than 200 000 years. This precise subdivision only appeared with the statistical analysis. The study of the electrofacies accordingly extended to the entire sector (Fig. 16).

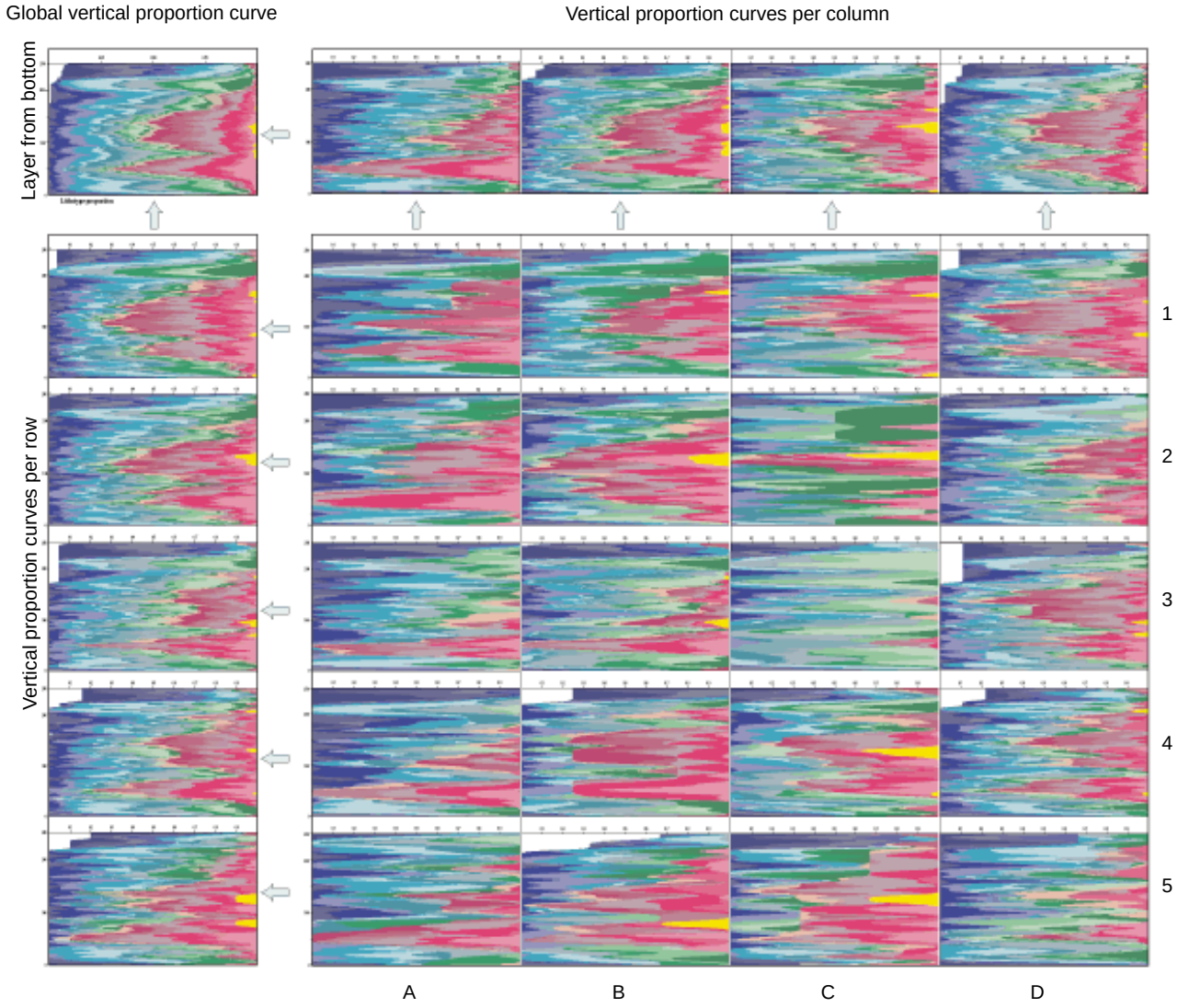

Figure 16

Pseudomatrix of proportions calculated on the entire sector (Ravenne *et al.*, 2000).

See color key Figure 15. The figure at top left represents the vertical proportion curve calculated with the 150 wells of the field. It shows in the dolomites (pink) a general bell shape, but with two maxima. These evolutions emphasize a strong vertical nonstationary, which is generally the case. The row above left presents the succession of proportion curves calculated in the latitudinal bands (1 to 5) 5 km wide. The wide variation in forms from one band to another emphasizes the strong horizontal nonstationary, which is also found in the band at top right of the general proportion curve. This curve shows the succession of proportion curves calculated in longitudinal bands (A to D) 6 km wide. The last figure (matrix A-D/1-5) shows the succession of proportion curves calculated in blocks A1, A2, etc. It reveals the detailed evolution from one block to another. Note however that the stratigraphic subdivision (emphasized by the succession of peaks) is perfectly observed in all the blocks and that it is a predominant factor for the reservoir properties.

The test of the reference marker initially determined by *AGIP* culminated in a very noisy overall vertical proportion curve, revealing no sequence evolution except in the upper portion of the series, close to the marker concerned. The inconsistencies identified could be caused by different behaviors of the different portions of the field, by a differential subsidence, or by the presence of unconformities. They were understood by the identification of the abnormal evolution of a level of lacustrine limestones located a few meters under the initial *AGIP* reference marker. Its initially zero thickness increased gradually to over 6 m. This evolution is impossible at the scale of a field unless it is highly compartmentalized and very different from the others. This lacustrine limestone level was tested as a datum level. The new overall proportion curve showed a clear evolution completely comparable to the perfectly controlled evolution

obtained in the Almedina site (*Fig. 7*). The evolution history could be reconstructed and different accommodation space identified. This new curve also helped to refine the shape of the series and, step by step, by testing new hypotheses, to individualize the series better and to distinguish the markers to be used for the calculations specific to each of them. The identification of the impact of the log acquisition period on the percentage of facies could then be determined thanks to several calculations of proportion curves that were performed, on the whole, by sectors and by lines, in the upper portion, with the facies derived from the logs of all the earlier wells, and also with the facies derived from the more recent wells (indeed, the logs had been homogenized and the calibration made on cored wells and with logs. The early wells had beenhided). The comparison of these curves showed the similarity of the forms and hence an identical sequence evolution, but it also revealed differences in percentages which could be substantial depending on the facies concerned. Thus a facies considered to be an excellent reservoir reached 30% at a given level on the curve plotted with one of the sets of logs and 60% with the other set for the same level

1.5.2 A "Giant" (Saudi Arabia, 1998)

One of the biggest "oil giants" is owned by *SAUDI ARAMCO*.

The problem was the presence of very powerful and localized inflows in very thin drains. The permeability of these drains could exceed some ten darcys. These water inflows were assumed to be connected with fracture networks. The aim was to simulate these networks by a multidisciplinary study.

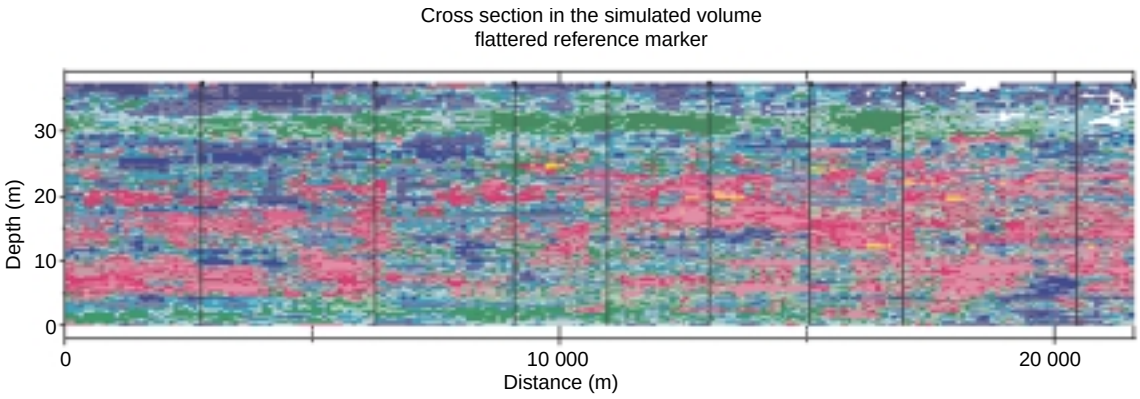

Figure 17

Section 2D extracted from a 3D electrofacies simulation (Ravenne *et al.*, 2000).

This figure emphasizes the strong horizontal variability of the electrofacies. Stratigraphic control is clear despite the wide disparity in scales.

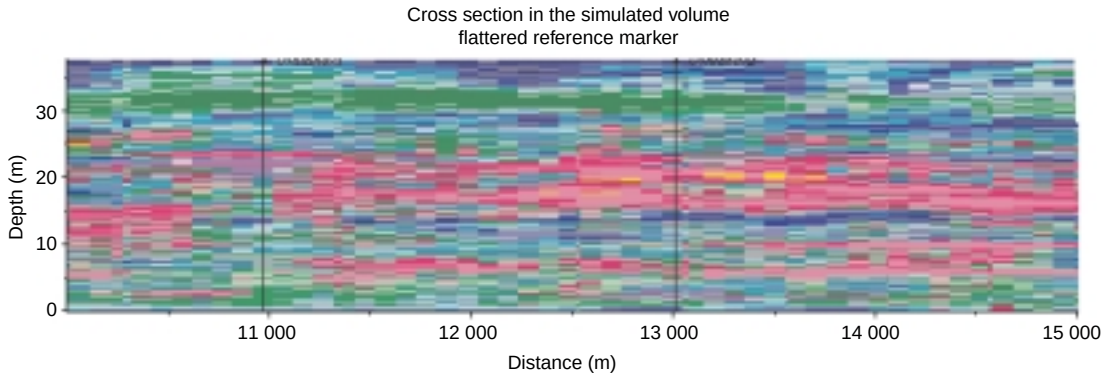

Figure 18

Detail of section 3D of Figure 17 (Ravenne *et al.*, 2000).

The scales are still quite different but the difference is smaller than in the previous figure, making it possible to emphasize the importance of stratigraphic control in the electrofacies distribution.

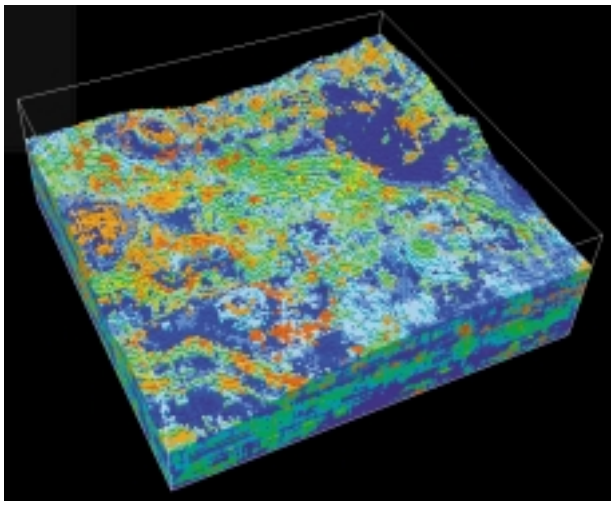

Figure 19

3D block representing the simulation in lithotypes (Ravenne *et al.,* 2000).

The simulation grid consists of 2.5 m sided meshes and 50 cm high. The orange zones are zones where reefs are present. The petrophysical properties of the matrix mainly influence the fluid content and the long term evolution.

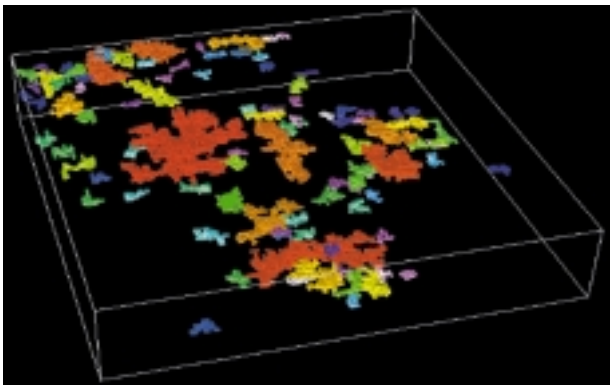

Figure 20

3D block representing the simulation of very high permeability zones (Ravenne *et al.,* 2000).

The different colors indicate the high permeability zones which are connected. Note that these zones are located along specific stratigraphic levels. The upward migration of these zones reflects the generalized transgression affecting the sector.

The objective was to simulate one of the reservoirs of this "giant" in one of the sectors where the water inflows became very harmful for production. The reservoir is located in the "Arab D" formation at the top of the Jurassic. It consists of highly bioclastic, indeed constructed limestones, alternating with micritic limestones. They were deposited in a shallow water depth, sometimes zero, and rarely more than 30 m. The platform where these sediments were deposited was very wide, with relatively weak paleotopographies. In such a setting, the least relative variation in thickness of the water depth has important repercussions for the marine flora and fauna, and is also reflected by large—amplitude diagenetic effects. The total duration of the interval investigated was about 1 Ma. One of the results from the study was to demonstrate, from proportion curves, the sequence and paleo-environmental evolutions (*Figs. 15 et 16*).

The tools employed to model the fracture network were the EasyTrace software (Fournier, 1997), Fraca software (Cacas *et al.,* 1994, 1997) and Heresim software (Rudkiewicz *et al.,* 1990; Doligez *et al.,* 1992b; Chautru *et al.,* 1993).

The final simulations made after a series of tests demonstrated a predominant stratigraphic control on the distribution of heterogeneities (*Figs. 17 and 18*).

Another problem concerned the homogenization of the data making up the final data processing phase before the use of the static model by the reservoir engineers. It was necessary to respect the size of the specific drains responsible for the water inflows, often less than 50 cm thick. This was resolved by using nested simulations allowing the homogenization of the matrix while preserving the high-permeability drains.

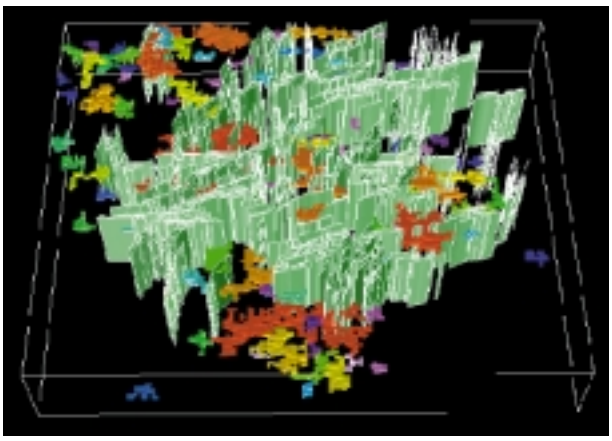

Figure 21

3D Block showing the superimposition of the high permeability zones and fracture networks (Ravenne *et al.,* 2000).

It is the total of these simulations and that of the matix which directs the fluid flow simulations. The results obtained, compared with the production record, were immediately conclusive, without having to adjust the n possible parmeters. These results demonstrate the power of a precise facies sedimentology and a high resolution sequence stratigraphy analysis supported by quantification tools.

Figures 19 to 21 show the final results of the simulations with, in Figure 19, the simulation of the matrix, Figure 20, the simulation of the high permeability drains (up to several darcys) and Figure 21, the result of the superimposition of the simulation of very high permeability drains and the simulation of the fracture network.

2 FUTURE WORK AND ANTICIPATED RESULTS

2.1 Short Term (One to Two Years)

The main research guidelines to be followed, at least in the medium term, are those implying the use and development of sedimentology and stratigraphy, as well as those aimed to broaden the multidisciplinary skills, particularly between geology, geochemistry, geophysics, geostatistics and reservoir. This aspect fits into the efforts conducted every year during which the author directed the reservoir characterization project.

One of these guidelines is always the understanding of the sedimentary processes in which a special effort, already well initiated, is made on the interactions between tectonics and sedimentation, and on the erosion, transport and deposition balances. These projects, like those discussed later, are important in terms of time and workload, and demand numerous collaborations and cooperations with the academic world. The modeling of the sedimentary fill, which owes considerably to the development of sequence stratigraphy concepts (in which the group actively participated) will be continued with a focus on submarine sedimentary deposits beyond the platform (submarine fans, slope deposits). The continued study of the Annot sandstones supplies the knowledge of the reservoirs of these environments and a number of constraints of the model. The investigation of other sites is already planned.

For many years, an attempt has been made to link the basin models with those of the reservoir in view of the reciprocal influences. The success rate has so far been mixed. A number of reasons for these failures have been clarified, several problems have been resolved, and this link becomes a priority for the short term. It will help in particular to more effectively include the diagenetic consequences of fluid circulations at the basin scale, consequences which are crucially important for the reservoir properties.

Reservoir modelings represent the main objective of the work done by the group during the last twelve years. From the outset of the project, it was planned to incorporate the dynamic constraints, *i.e.* those provided by the production data. This was not possible for several years. Progress achieved in reservoirs, particularly by the *IFP* group in Pau led by Blanc and Noetinger, ensure that their consideration can be effective in the short term. The last four years made it possible to start taking account of the seismic constraints and significant results were obtained (Doligez *et al.*, 1999a, 1999b). This work must be continued since the seismic information content is extremely rich and still insufficiently used in our modeling methods. Progress in seismic acquisition and in processing continues at a steady rate, making it necessary to ensure their future use, and especially repetitive shooting (4D).

One more guideline deserves mention: the participation of the models and geological knowledge in the drilling of interactive boreholes. The aim is to take account, in real time, of the information obtained during drilling to update the sedimentological constraints and models, and thereby modify and clarify the rest of the borehole. This guideline is extremely important for the optimization of complex wells. This project had been considered two years ago (1998). A number of problems, some of them algorithmic, led to its postponement. The lifting of some of them should help to obtain a prototype in the short term.

The main objectives are obviously of an economic order and are virtually the same as those discussed in the beginning of this article. The aim is to optimize the knowledge and thereby the production of reservoirs (with a very strong focus on all the heterogeneities associated with the stratigraphic setting, but also ensuring close cooperation with structural, diagenetic and geochemical models) so as to reduce the costs and increase the recovery rates. The improvement in reservoir knowledge, particularly in the marine domain, reduces many risks and therefore has a definite impact on environmental conservation. This point has always been a strong argument during each of the projects presented to the European Union. The scientific objectives derive from each of the guidelines and the multidisciplinary projects. Special attention is paid to those aimed to improve knowledge and the stratigraphic and sedimentological modelings in the carbonate and deep sea domains.

All these guidelines will be pursued in the medium term, and some of them during the long term.

Although this project was launched in 1986, it continues with steady progress and substantial results. The guidelines presented above are equally important.

2.2 Medium Term (Four Years) and Long Term (Ten Years)

These projects are lumped together in the same section because is would seem that they should be initiated rapidly, that results can be obtained in the medium term, but that their scope encourages their consideration as necessary over the long term. These projects primarily concern those associated with reservoir characterization and hence the prediction of the lithologies and heterogeneities. The sequence stratigraphy tool prove to be very effective and indispensable. Field studies allowed a significant advance in the concepts, but

were nonetheless focused on analogues of real reservoirs and are hence relatively scattered in the chronostratigraphic scale and in the sequencing of the orders. It now seems necessary to undertake systematic studies targeted on key periods corresponding to the maximum and minimum of the curves of sea level variations over a 2nd order cycle. Two periods should be examined first: one dominated by warm temperatures and one comprising abundant glacial phases.

More specifically, the aim is to determine the geometric evolution of the sequences and their constitution by a 5th order scale analysis (Goldhammer *et al.*, 1990; Guillocheau, 1991; Mitchum and Van Wagoner, 1991; Vail *et al.*, 1991; Van Wagoner *et al.*, 1990, etc.), first of the characteristics of the two 5th order sequences deposited one when all the maxima (2nd order to fifth order) are superimposed, and the second when all the minima are superimposed. This characterization will then be extended to the over and underlying sequences not only to identify the effects of phasings and successive phase of oppositions between the different orders in the eustatic variations. In the longer term, a similar study should also be conducted on the characterizations of sequences near the inflexion point of the change in sea level of the 2nd order. The anticipated results are to obtain reliable laws for the prediction of the geometries and deposits allowing a more rigorous modeling, and obviously a better understanding, and facilitating the deciphering of the sedimentary series.

This project should be conducted in priority in environments where these sequences are well preserved, such as the outer platform margins, and then can be extended to slope and basin environments on the one hand, and littoral coastal and continental environments on the other. The scale of this work means that its accomplishment will demand broad cooperation and could (should?) fit into the framework of a major national/international project. It will also be an opportunity to reinforce the multidisciplinary teams.

The situation report of the *French National Committee for Scientific Research* (Cara *et al.*, 1996) has already been mentioned for the stratigraphy, sedimentology and biodiversity part to which Deynoux, Marcoux, de Wever and the author particularly contributed. The definition of the environments is fundamentally important for predicting and modeling sedimentary bodies. It is very difficult once the available information becomes fragmentary (which is often the case with borehole data). Only a few disciplines are combined. It is here that the situation report is resumed: each discipline can advance considerably within the frameworks provided by high resolution sequence stratigraphy while also contributing to its evolution. This is one of the tasks to which the author wants to contribute in the medium term, first with the development of closer synergies with the inorganic, organic and isotopic geochemistries. The results expected are the acquisition of new discriminating parameters for the definition of the environments. In the longer term, these parameters should participate in the resolution of two crucial problems: the determination of the paleoaltitudes and paleobathymetries and the problem of geological time and precise durations of deposits and nondeposition periods.

2.3 If the Possibility Arises

In order to procure immediately resources not applied to the objectives listed above, several subjects could be proposed for PhD dissertations, which would be useful for them and which would participate in advancing the knowledge affecting stratigraphy; given the industrial prospects, these dissertations would have favorable prospects for their professional integration. These projects would address problems and challenges that have been mentioned on several occasions in the body of this article:

- The precise role of sedimentation hiatuses, condensation surfaces and very low sedimentation rate layers on the genesis of the reflections. These challenges are enormous: creation of new interpretation methods and new processing algorithms. The link with stratigraphy is that these developments would allow the increased utilization of the seismic data, particularly marine, which are the only data to offer vertically and laterally continuous records of the sedimentary history.
- The reinterpretation of the Cap-Ferret and Bahamas sites. These subjects are justified by the revival of interest in submarine fans at the foot of stable margins, both from the economic and scientific standpoint as emphasized by the creation of the GDR “Margins”. Secondly, the data from these two sites are of excellent quality, and it seems improbable that a similar acquisition effort can be made in the near future, and the author anticipates the results that will be obtained with the inclusion of current concepts and remembering the qualitative leap achieved by Lafont-Pétassou (1993) when she resumed the study of the profiles of the Indus site. These seismic interpretation tasks should be accompanied by field studies since they are indissociable both in terms of their reciprocity and their contributions.
- The resumption of channel and tank experiments.

CONCLUSIONS

As introduced in the foreword, all the projects completed were guided by stratigraphy. Their execution was made possible within *IFP* by numerous cooperative ventures set up with the academic and industrial worlds. Considerable progress has been made in seismic stratigraphy and sequence stratigraphy, and this should continue in view of the scale of the work to be done and the synergies to be developed. The author wishes to underscore the salient facts of his last phase of activity at *IFP*.

His team was among the first to address the adventure of introducing a quantified geology to characterize the heterogeneities of underground reservoirs. The needs were expressed very powerfully at the international level by most of the persons involved. The risks, costs and challenges were real and substantial. Less than three years after the outset of the project, the team earned international recognition (1987, 1988).

The methodology, particularly with the integration of the disciplines and the way to handle the problems, was recognized, giving rise to invitations by many companies and universities. The method took longer to be accepted and still today, it is not universally popular although many university and industrial researchers have drawn their inspiration from them. In fact, other groups of researchers very soon worked on this theme to take position in a promising market. The strong point of the *IFP/ARMINES* group is a real consideration of the geology in the approach, the analysis of the data and the simulation methods. The work done helps to revive the French needs for sedimentology and stratigraphy both in the academic and industrial fields. This projects was the starting point for many detailed field studies in sequence stratigraphy to respond to needs for reservoir characterization. These studies culminated in the improvement and creation of new concepts in sequence stratigraphy formalized and circulated essentially by Homewood *et al.* (1992), Homewood and Eberli (2000) and Guillocheau (1995) for outside cooperation by Eschard (Eschard, 1989; Eschard *et al.*, 1991, 1993, 1998) and Van Buchem (Van Buchem *et al.*, 2000a and 2000b).

The work completed led to the industrialization and marketing of the Heresim software developed jointly by *IFP* and *ARMINES* with the participation of *GEOVARIANCES*. This software has since then been enriched (also by joint research between *IFP* and the *Centre de géostatistiques* of the *ENSPM*), interalia, by the consideration of seismic constraints with the participation of Richard (Déquirez *et al.*, 1992) and Fournier (Fournier, 1995; Beucher *et al.*, 1999; Ravenne *et al.*, 1996; Eschard *et al.*, 1998; Fichtl *et al.*, 1997; Johann *et al.*, 1996)—Thermie project in collaboration with *AGIP*—the consideration of the horizontal nonstationary, the introduction of new geostatistical methods like the Boolean really conditioned to the wells or the multi-Gaussians. The introduction of these new methods led to the establishment of new databases ensuring their effective use and hence new field studies or the resumption of previous studies to acquire the parameters required by these methods.

In the final chapter, the author presented the research projects in which he wants to be involved, listing those of general scope in which he wants to participate in their promotion and execution. The aim is still to decipher the sedimentary message. The priorities concern the approaches and definitions of the deposition and nondeposition durations, both of the paleobathymetries and paleoaltitudes, and the implementation of real synergies between the different disciplines present in the field of earth science, but which should also associate those of several other areas. The climate with an impact on the sedimentary message should also be the subject of intensive research. Importance must be laid on work to be done and the results obtained in the field of biodiversity which constitutes the indispensable prerequisite to future projects.

Finally, it is necessary to make a stronger commitment to cooperation between the various organizations, because it is indispensable to complete the future projects with all the forces required, and which should be the subject of national and European projects initially, with a broader opening to the rest of the world community subsequently.

ACKNOWLEDGEMENTS

The work discussed in this review was achieved mainly thanks to the *IFP*'s scientific, technical and financial support. The major projects and extensive studies conducted were also backed by the EEC (*Basis of Heresim 2D, supported by EC TH 01.070/86 from 1986 to 1990; validation of the Heresim methodology and 3D software supported by EC OG/0097/FR/IT, from 1991 to 1994; quantification reservoir modeling constrained by wells and seismic data supported by EC project OG/115/95 from 1995 to 1998)* and by several organizations *(DHYCA* with *FSH*) and/or companies *(ELF, AGIP, GDF, MARAVEN, PETROBRAS, SAUDI ARAMCO, SONATRACH, TOTAL*, etc.). The meaning of acronyms is provided at the end of the text.

Virtually all the work was done in often close cooperation with researchers of the *École nationale supérieure des mines* de Paris (A. Galli, H. Beucher, C. de Fouquet, C. Lantuéjoul, G. Le Loc'h, G. Matheron, J. Rivoirard, S. Séguret et H. Wackernagel), various universities (F. Guillocheau, JP. Loreau, etc.) and with engineers (whose names are given with the studies) of several companies. Very early, they involved multidisciplinary groups. Also noteworthy was the active participation of numerous students of the *ENSPM* during their final year courses, DEA diploma and PhD dissertations.

The work done at *IFP* was initiated by L. Montadert. All the studies described in this paper were completed in close cooperation with many *IFP* researchers: R. Eschard, B. Doligez, P. Joseph, G. Désaubliaux, O. Lerat, D. Granjeon, JC. Lecomte, Y. Mathieu, JL. Rudkiewicz, F. Van Buchem, LY. Hu, D. Guérillot, F. Fournier, P. Houel, P. Lemouzy, J.M. Daniel are those with whom the projects of the last ten years were achieved. Many thanks have to be expressed to L. Cosentino, Y. Coury, D. Camus, J.M. Chautru and J. Burrus of *BEICIP-FRANLAB* and to J. Cole from *SAUDI ARAMCO* with whom the last study on a "giant" in Saudi Arabia was carried out.

Finally, the author wants to thank N. Doizelet, Y. Calot-Martin, P. Le Foll, D. Deldique, M. Jehl, J. Brumaud, E. Jacquet, J.C. Sabathier, E. Gross and W. Choueiri for their essential technical assistance.

REFERENCES

Beucher, H., Geffroy, F. and Doligez, B. (1997) Introducing more geology in reservoir stochastic modelling using truncated gaussian approach. In *Sedimentologia*, 1° congreso latinoamericano, Porlamar, 16-19 Nov. 1997, Mem., **1**, 89-95.

Beucher, H., Fournier, F., Doligez, B. and Rozanski, J. (1999) Using 3D seismic derived information in lithofacies simulations. A case study. In *Annual Technical Conference and Exhibition of the Society of Petroleum Engineers*, Proceedings: Formation Evaluation and Reservoir Geology, SPE 56736, Houston, 3-6 Oct. 1999, 581-592.

Boudjéma, A. (1987) Évolution structurale du bassin pétrolier «Triasique» du Sahara nord occidental (Algérie). *Thèse de doctorat*, Paris XI Orsay.

Busson, G. (1970) *Le Mésozoïque saharien, 2e partie : Essai de synthèse des données des sondages algéro-tunisiens*, tome 2, Éds du CNRS, série C, Sci. de la Terre, T XXVI, Paris.

Busson, G. (1972) *Principes, méthodes et résultats d'un étude stratigraphique du Mésozoïque saharien, 2e partie*, Éds du CNRS, série Géol.,11, Paris.

Cacas, M.C. and Letouzey, J. (1994) Fracas: a new tool for modeling fractured reservoir geometry. In *GEO 94, The Middle East Geosciences Exhibition and Conference*, Bahrain, 25-27 April.

Cacas, MC., Bourbiaux, B., Sarda, S. and Sabathier, JC. (1997) How turn the geological image of a fractured reservoir into a dual-porosity model. *AAPG Intern. Conf.*, Vienna.

Cara, M., Armijo, R., Bouchez, JL, de Wever, P., Deynoux, M., Dupre, B., Karczewski, J.F., Malod, J., Manoussis, E., Marcoux, J., Mascle, G., Maury, R., Monod, O., Moreau, C., Moullade, M., Perroud, H., Ravenne, C., Respaut, J.P., Reynier, B., Ruellan, E. and Villeneuve, M. (1996) Planète Terre : structure, histoire et évolution. In *Rapport de conjoncture du Comité national de la recherche scientifique*, Éds du CNRS,173-183.

Chautru, J.M., Ravenne, C., Lemouzy, P. and Galli, A. (1993) Heresim 3D: integrating data and disciplinaries for reservoir characterization. In *Oil and Gas Technology in a Wider Europe*, Proceedings of the 4th EC Symposium, 3-5 Nov. 1992, Berlin. Aberdeen, the Petroleum Science and Technology Institute, 415-427.

Deegan, C.E. and Scull, B.H. (1977) A proposed standard lithostratigraphic nomenclature for the central and northern North Sea. *Rep. Inst. Geol. Sci. Bull.*, 77/25, NPD 1.

Déquirez, P.Y., Fournier, F. and Richard, V. (1992) The advantage of using calibrated and integrated processing for a better reservoir description. In *WPC-13th World Petrleum Congress*, Buenos-Aires, 20-25 Oct. 1991, Proceedings, **2**, 487-495, John Wiley and sons Limited, Chichester, 1992.

Doligez, B., Eschard, R., Ravenne, C., Galli, A., Guérillot, D. and Heresim Group (1992a) Fundamental geologic and geostatistical concepts and tools for reservoir characterization. In *Oil and Gas Technology in a Wider Europe*, Proceedings of the 4th EC symposium, Berlin, 3-5 Nov., 728.

Doligez, B., Ravenne, C., Lemouzy, P. and Galli, A. (1992b) Une méthodologie pour une étude intégrée des réservoirs. Des données de puits aux simulations d'écoulement en utilisant des outils géostatistiques. *Pétrole et Techniques*, 372, 43-47.

Doligez, B., Beucher, H., Fonnesu, F., Tebaldi, E. and Baruffini, L. (1994), Construction and visualization of the reference models of Cajigar. In *Modeling the Earth for Oil Exploration*, K. Helbig Ed., Pergamon, 81-91.

Doligez, B., Beucher, H., Geffroy, F. and Eschard, R. (1999a) Integrated reservoir characterization: improvement in heterogeneities stochastic modelling by integration of additional external constraints. In *Reservoir Characterization-Recent Advances*, Schatzinger and Jordan Eds., AAPG Mem. 71, 333-342.

Doligez, B., Beucher, H., Geffroy, F., Eschard, R. and Guérillot, D. (1999b) Uncertainties in reserves estimations: sensitivity to geostatistical parameters. In *Ingepet'99, 3rd International Seminar on Exploration and Exploitation of Petroleum and Gas*, Lima, 26-29 Oct. 1999, Proceedings.

Eschard, R. (1989) Géométrie et dynamique de séquences de dépôts dans un système deltaïque (Jurassique moyen, bassin de Cleveland, Angleterre). Implications sur l'architecture tridimensionnelle des corps sédimentaires. *Thèse*, université Louis Pasteur, Strasbourg,.

Eschard, R., Ravenne, C., Houel, P. and Knox, R. (1991) Three-dimensional reservoir architecture of a valley-fill sequence and a deltaic aggradational sequence: influences of minor relative sea-level variations (Scalby Formation, England). In *The Three-Dimensional Facies Architecture of Terrigenous Clastic Sediments and its Implications for Hydrocarbon Discovery and Recovery*, A.D. Miall, Tyler Eds., SEPM, Concepts in Sedimentology and Paleontology, **3**, 133-147.

Eschard, R., Tveiten, B., Désaubliaux, G., Lecomte, J.C. and Van Buchem, F. (1993) High-resolution stratigraphy and reservoir prediction of the Brent Group (Tampen Spur Area) using an outcrop analogue (Mesa Verde Group, Colorado). In *Subsurface Reservoir Characterisation from Outcrops Observations*, Proc. 7th IFP Explor. Prod. Res. Conf. (1992), R. Eschard and B. Doligez, Eds., Éditions Technip, Paris, 35-52.

Eschard R., Lerat O., Granjeon D., Doligez B., Désaubliaux G. and Lafont F. (1997) Predicting genetic sequence architecture of eolian/fluvial systems in North Sea reservoirs from an outcrop model (Cutler Fm., Permian, USA), *AAPG Int. Conf.*, Vienna.

Eschard, R., Désaubliaux, G., Durand, C., Ravenne, C. and Hamel, A. (1998a) Second year and final report of the consortium "Regional synthesis of the Triassic reservoir in Algeria". *IFP Research Report* no. 44350, Rueil-Malmaison.

Eschard, R., Fournier, F., Guérillot, D., Montadert, L., Noetinger, B. and Ravenne, C. (1998) New technologies improve the prediction of reservoir quality during the appraisal of a field. In *WPC-15th World Petrol. Cong.*, Beijing, 1-16 Oct. 1997, Proceedings, **2**, 241-242, John Wiley and Sons, 1998.

Fichtl, P., Fournier, F. and Royer, J.J. (1997) Cosimulations of lithofacies and associated reservoir properties using well and seismic data. In *SPE 72nd. Ann. Techn. Conf. and Exhibition of the Soc. of Petrol. Eng.*, Dallas, 5-8 Oct. 1997, Proceedings, Part 1, 381-393, SPE 38680.

Fonnesu, F., Tebaldi, E. and Baruffini, L. (1994) Geological presentation of the Cajigar outcrops. In *Modeling the Earth for Oil Exploration*, K. Helbig Ed., Pergamon, 31-38.

Fouquet, de C., Beucher, H., Galli, A. and Ravenne, C. (1989) Conditional simulation of random sets - Application to an argilaceous sandstone reservoir. *3rd International Geostatistics Congress*, Avignon, 5-9 Sept. 1988, M. Armstrong Ed., *Geostatistics*, **2**, Kluwer Academic Publishers, Dordrecht, 517-530.

Fournier, F. (1995) Integration of 3D seismic data in reservoir stochastic simulations: a case study. In *SPE-Formation Evaluation and Reservoir Geology*. Ann. techn. conf. and exhibition of the Soc. of Petrol. Eng., Dallas, 22-25 Oct. 1995, Proceedings, 343-356, SPE 30564.

Fournier, F. (1997, 1998) Méthodes statistiques et classement d'événements liés aux propriétés physiques d'un milieu complexe tel que le sous-sol. *Brevets* n° 97/12.182 France et n° 157/572 USA 210998 étranger.

Galli, A., Guerillot, D., Ravenne, C. and Heresim Group (1990) Combining geology, geostatistics and multiphase fluid flow for 3D reservoir studies. In *2nd European Conference on the Mathematics of Oil Recovery*, Arles, 11-14 Sept. 1990, D. Guérillot and O. Guillon, Éditions Technip, Paris,11-19.

Galli, A. and Ravenne, C. (1995) Reservoir characterization combining geostatistics and geology: part 2. In *AAPG International Conference and Exhibition*, 10-13 Sept. 1995, Nice.

Goldhammer, R.K., Dunn, P.A. and Hardie, L.A. (1990) Depositional cycles, composite sea-level changes, cycle stacking patterns, and the hierarchy of stratigraphic forcing: example from Alpine Triassic platform carbonates. *Geol. Soc. Amer. Bull.*, **102**, 535-562.

Granjeon, D. (1997) Modélisation stratigraphique déterministe : conception et applications d'un modèle diffusif 3D multi-lithologique. *Thèse de doctorat*, université de Rennes (1996). Mém. 78 de Géosciences Rennes.

Granjeon, D. and Joseph, P. (1999) Concepts and applications of a 3-D multiple lithology, diffusive model in stratigraphic modeling. In *Numerical Experiments in Stratigraphy: Recent Advances in Stratigraphic and Sedimentologic Computer Simulations*, SEPM special publ., 197-210.

Groult, J. (1970) Étude de la répartition des corps sableux dans les dépôts de type fluvio-lagunaire, *Petropa. Internal Report* 16194.

Guérillot, D., Rudkiewicz, J.L., Ravenne, C., Renard, G. and Galli, A. (1989) An integrated model for computer aided reservoir description: from outcrop study to fluid flow simulations. In *Proceedings of the 5th European Symposium on Improved Oil Recovery*, Budapest, 25-27 April 1989, 651-660.

Guérillot, D., Lemouzy, P., Galli, A. and Ravenne, C. (1990a) 3D fluid flow behavior in porous media characterized by geostatistical method. In *Soc. Petrol. Eng. Latin American Petroleum Engineering Conference and Exhibition*, Rio de Janeiro, 14-19 Oct. 1990, SPE 21081.

Guérillot D., Rudkiewicz J.L., Ravenne C. and Renard G. (1990b) An integrated model for computer aided reservoir description: from outcrop study to fluid flow simulations. *Rev. Inst. Fr. Pétrole*, **45**, 1, 71-77.

Guérillot, D., Lemouzy, P. and Ravenne, C. (1991) How reservoir characterization can help to improve production forecasts. In *Improved Oil Recovery, 6th European Symposium*, Stavanger, 21-23 May 1991, Proceedings, 3-12.

Guillocheau, F. (1991) Modalités d'empilement des séquences génétiques dans un bassin de plate-forme (Dévonien armoricain) : nature et distorsion des différents ordres de séquences de dépôts emboîtés. *Bull. Centres Rech. Explor.-Prod. Elf Aquitaine*, **15**, 2, 383-410.

Guillocheau, F. (1995) Nature, rank and origin of phanerozoic sedimentary cycles, *C.R. Acad. Sci. Paris*, **320**, série II a,1141-1157.

Homewood, P.W., Guillocheau, F., Eschard, R. and Cross, T.A. (1992) Correlations haute-resolution et stratigraphie génétique : une démarche intégrée. *Bull. Centre Rech. Explor.-Prod. Elf Aquitaine*, **16**, 357-382.

Homewood, P.W. and Eberli, G.P. (2000) Genetic stratigraphy on the exploration and production scales - Case studies from the Pennsylvanian of the Paradox basin and the Upper Devonian of Alberta. *Bull. Centre Rech. Elf Explor.-Prod.*, Pau, Mém. **24**.

Houel, P., Lamiraux, C., Mathieu, Y. and Heresim Group (1991) Étude sédimentologique préparatoire à l'analyse géostatistique du Trias supérieur, *IFP Research Report* no. 38591, Rueil-Malmaison.

Hu, L.Y., Joseph, P. and Dubrule, O. (1992) Random genetic simulation of the internal geometry of deltaic sandstone bodies, *In SPE 67th Annual Tech. Conf. and Exhibition of the Soc. of Petroleum Engineers*, Washington, 4-7 Oct., Proceedings, 535-544

Jacquin, C., Henriette, A., Guérillot, D. and Adler, P.M. (1991) Heterogeneity and effective permeability of porous rocks: experimental and numerical investigation. In *Reservoir Characterization II*, L.W. Lake *et al.* Eds., 662-664, Academic Press Inc., New York.

Johann, P., Fournier, F., Souza-Jr., O., Eschard, R. and Beucher, H. (1996) 3D stochastic reservoir modeling constrained by well and seismic data on a turbidite field. In *SPE-71st Ann. Techn. Conf. and Exhibition of the Soc. of Petrol. Eng.*, Denver, 6-9 Oct. 1996, Proceedings, 51-66, SPE 36501.

Joseph, P. and Dubrule, O. (1994) Construction and visualization of the reference models of Roda. In *Modeling the Earth for Oil Exploration*, K. Helbig Ed., Pergamon, 61-78.

Lafont-Petassou, S. (1993) Géométrie des séquences de dépôt à la limite continent-océan : exemple de la marge pakistanaise. *Thèse*, université Paris XI Orsay.

Langlais, V., Doyle, J.D., Sweet, M.L. and Geehan, G.W.(1993) An additional geological input to the sequential indicator simulation (SIS.): the vertical organization of lithofacies. In *Subsurface Reservoir Characterisation from Outcrops Observations -Proc. 7th IFP Explor. Prod. Res. Conf.* (1992) R. Eschard and B. Doligez Eds., Éditions Technip, Paris, 111-123.

Lasseter, T.J., Waggoner, J.R. and Lake, L.W. (1986) Reservoir heterogeneities and their influence on ultimate recovery. In *Reservoir Characterization*, L.W. Lake and H.B.C. Carroll, Jr Eds., Academic Press, Orlando, USA, 545-560.

Lawrence, D.T., Doyle, M. and Aigner, T. (1990) Stratigraphic simulation of sedimentary basins: concepts and calibration. *Bull. Amer. Assoc. Petroleum Geol.*, 74, 273-295.

Lerche, I. (1989) Philosophies and strategies of model building. In *Quantitative Dynamic Stratigraphy*. T.A. Cross. Ed., Prentice Hall, Englewood Cliffs, New Jersey, 21-44.

Lesueur, J.L., Claude, D., Dubrule, O., Soudet, H. J., Joseph, P. and Crumeyrolle, P. (1994) Geological presentation of the Roda sandstone. In *Modeling the Earth for Oil Exploration*, K. Helbig Ed., Pergamon, 26-31.

Matheron, G., Beucher, H., De Fouquet, C., Galli, A., Guérillot, D. and Ravenne, C. (1987) Conditional simulation of the geometry of fluvio-deltaic reservoirs. In *62nd Ann. Techn. Conf. and Exhibition of the Soc. Petrol. Eng. of AIME*, Proceedings, Dallas, 27-30 Sept.1987, Soc. Petrol. Eng. 16753, 591-599.

Matheron, G., Beucher, H., De Fouquet, C., Galli, A. and Ravenne, C. (1988) Simulation conditionnelle à trois faciès dans une falaise de la formation du Brent - Séminaire sur la géostatistique, Fontainebleau, 15-16 juin 1988. *Sci. de la Terre*, série *Informatique géologique*, 28, 213-249.

Mathieu, Y., Verdier, F., Houel, P., Delmas, J. and Beucher, H. (1993) Reservoir heterogeneity in fluvial Keuper facies: a subsurface and outcrop study. In *Subsurface Reservoir Characterisation from Outcrops Observations - Proc. 7th IFP Explor. Prod. Res. Conf.* (1992) R. Eschard and B. Doligez Eds., Éditions Technip, Paris, 145-160.

Mitchum, R.M. and Van Wagoner, J.C. (1991) High-frequency sequences and their stacking patterns: sequence-stratigraphic evidence of high-frequency eustatic cycles. *Sed. Geol.*, **70**, 131-160.

Montadert, L., Verrien, J.P. and Couraud, G. (1966a) Application des méthodes de géologie de production à l'analyse des propriétés réservoirs à partir des affleurements. CMP Mexico April 1967. *IFP Research Report* no.13753, Rueil-Malmaison.

Montadert, L., Fondeur, C., Vachey, G., Bouche, P. and Groult, J. (1966b) Utilisation de core drills proches des affleurements pour l'étude d'un réservoir argilo-gréseux. *IFP Research Report* no. 13960, Rueil-Malmaison,.

Préat, A. and Mennig, J.J. (1994) Geological presentation of the Poulseur/Bois d'Anthisnes quarries. *In* Modeling the earth for oil exploration, K. Helbig ed., Pergamon, 39-43.

Ravenne, C. and Beghin, P. (1983) Apport des expériences en canal à l'interprétation sédimentologique des dépôts de cônes détritiques sous-marins. *IFP Research Report*, **38**, 3, 279-297.

Ravenne C. and Beucher H. (1988a) Recent development in description of sedimentary bodies in a fluvio deltaic reservoir and their 3D conditional simulations. *In 63rd Ann. Techn. Conf. and Exhibition of the Soc. of Petroleum Eng.*, Houston, 2-5 Oct.1988, Proceed., Soc. Petrol. Eng. 18310, 463-476.

Ravenne, C., Eschard, R., Galli, A., Mathieu, Y;, Montadert, L. and Rudkiewicz, J.L. (1988b) Geometry and geophysical properties of sedimentary bodies deposited in a fluvio-deltaic environment. In *Quantification of Sediment Geometries and their Internal Heterogeneities*, London.

Ravenne, C., Eschard, R., Galli, A., Mathieu, Y., Montadert, L. and Rudkiewicz, J.L. (1989) Heterogeneities and geometry of sedimentary bodies in a fluvio-deltaic reservoir. *Soc. Petrol. Eng. Formation Evaluation*, June, 239-246.

Ravenne, C., Beucher, H., Mathieu, Y., Lamiraux, C. and Heresim Group (1990) Modèle de simulation des hétérogénéités de réservoir, rapport technique final du contrat CEE/GERTH n° TH 01.070/86, *IFP Research Repor*, no. 37623, Rueil-Malmaison.

Ravenne, C., Galli, A., Beucher, H., Eschard, R., Guerillot, D. and Heresim Group (1991) Outcrop studies and geostatistical modelling of a middle Jurassic Brent analogue. In *The European Oil and Gas Conference*, Palermo, Sicily, 9-12 Oct. 1990, G. Imarisio, M. Frias, J.M. Bemtgen Eds., Graham and Trotman, 497-520.

Ravenne, C., Galli, A. and Préat, A. (1994) Construction and visualization of the reference models of Poulseur/CBA. In *Modeling the Earth for Oil Exploration*, K. Helbig Ed., Pergamon, 91-96.

Ravenne, C. and Galli, A. (1995a) Reservoir characterization combining geostatistics and geology: part 1. In *Am. Assoc. Petroleum Geol. International Conference and Exhibition*, 10-13 Sept. 1995..

Ravenne, C., Joseph, P. and Gomes De Souza, O. (1995b) Classic Annot sandstones: seismic scale exposures of Eocene basinal turbidites in the french external Alps. *Am. Assoc. Petrol. Geol. International Conference and Exhibition*, Nice, 10-13 Spet.1995. Field Trip.

Ravenne, C., Doligez, B., Eschard, R., Galli, A., Guérillot, D. and Fournier, F. (1996) Reservoir characterization "methodology based on integration of sequence stratigraphy, geostatistics, reservoir engineering and geophysics". In *AAPG/ASPG-Research Symposium on Oil and Gas Petrol. Systems in Rapidly Subsiding Basins*, Abst., Baku, 6-9 Oct. 1996.

Ravenne, C., Cole, J., Cosentino, L. and Coury, Y. 2000. Characterization of reservoir heterogeneities and super permeability thief zones in a major oilfield in the Middle East. In *WPC 16th World Petroleum Congress*, Calgary, 11-15 June 2000, Proceedings, CD, ITS 604.

Ravenne, C. (2002) Stratigraphy and oil: a review. Part 1: Exploration and seismic stratigraphy: observation and description. *Oil and Gas Science and Tech.*, **57**, 3, 211-250.

Ravenne, C., Galli, A., Doligez, B., Beucher, H. and Eschard, R. (under printing) *Quantification of Facies Relationships via Proportion Curves*, Kluwer Eds.

Rudkiewicz, J.L., Guérillot, D., Galli, A. and Heresim Group (1990) An integrated software for stochastic modelling of reservoir. Lithology and property with an example from the Yorkshire middle Jurassic. In *North Sea Oil and Gas reservoirs II*, The Norwegian Institute of Technology, Graham and Trotman Eds., London. 399-406.

Stefani, M. and Van Buchem, F. (1997) Evolution of carbonate platforms and basins in the Middle Triassic of the Italian dolomites and its implications for the petroleum system. *IFP Research Report* no. 42844, Rueil-Malmaison,.

Vail, P.R., Audemart, F., Bowman, S.A., Eisner, P.N. and Perez-Cruz, C. (1991) The stratigraphic signatures of tectonics, eustacy and sedimentology, an overview. In *Cycles and Events in Stratigraphy*. Einsele G. *et al.* Eds., Springer Verlag, Berlin, Heidelberg, 617-659.

Van Buchem, F.S., Doligez, B., Eschard, R., Lerat, O., Grammer, G. M. and Ravenne, C. (2000a) Stratigraphic architecture and stochastic reservoir simulation of a mixed carbonate/siliciclastic platform (upper Carboniferous, Paradox basin, USA). In *Genetic Stratigraphy on the Exploration and Production Scales - Case Studies from the Pennsylvanian of the Paradox Basin and the Upper Devonian of Alberta*. P. Homewood and G. Eberli Eds., *Bull. Centre Rech. Elf Explor.-Prod.*, Pau, Mém. 24, 109-129.

Van Buchem, F.S., Chaix, M., Eberli, G.P., Whalen, M.T., Masse, P. and Mountjoy, E.W. (2000b) Outcrop to subsurface correlation of the Upper Devonian (Frasnian) based on the comparison of Miette and Redwater carbonate buildup margins. In *Genetic Stratigraphy on the Exploration and Production Scales - Case Studies from the Pennsylvanian of the Paradox Basin and the Upper Devonian of Alberta*. P. Homewood and G. Eberli Eds., *Bull. Centre Rech. Elf Explor.-Prod.*, Pau, Mém. 24, 225-267.

Van Wagoner, J.C., Mitchum, R.M. Jr., Campion, K.M. and Rahmanian, V.D. (1990) Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: concepts for high-resolution correlation of time and facies. *Amer. Assoc. Petroleum Geol.*, Methods in Exploration Series, **7**.

Verrien, J.P., Couraud, G. and Montadert, L. (1967) Application of production geology methods to reservoir characteristics analysis from outcrop observations. *Proc. Seventh World Pet. Cong.*, Mexico, 425-446.

Vollset, J. and Dore, A.G. (1984) A revised Triassic and Jurassic lithostratigraphic nomenclature for the Norwegian North Sea. *Norwegian Petrol. Directorate Bull.*, **3**.

Volpi, B., Galli, A. and Ravenne, C. (1997) Vertical proportion curves: a qualitative and quantitative tool for reservoir characterization. In *Sedimentologia*. 1° congreso latinoamericano, Porlamar, 16-19 Nov.1997, Mem. **2**, 351-358.

Weber, K.J. (1986) How heterogeneity affects oil recovery. In *Reservoir Characterization*, L.W. Lake and H.B.C. Carroll Jr Eds., Academic Press, Orlando, USA, 487-544.

Wright, R. (1986) Cycle stratigraphy as a paleogeographical tool: Point Lookout sandstone, southeast San Juan Basin, New Mexico. *Geol. Soc. Amer. Bull.*, 96, 661-673.

Final manuscript received in june 2002

ABOUT THE AUTHOR

Christian Ravenne is a geologist in the *Institut français du pétrole (IFP)*. He joined *IFP* in 1972 after completing his M.S. degree in applied geophysics in *La Sorbonne University* (Paris) in 1968 and his degree from the *École nationale supérieure des pétroles et des moteurs (ENSPM*, in both

geology and geophysics) in 1970. He has obtained the french diploma « Habilitation à diriger des recherches » of *Paris VI University*. He has been Project Manager for Reservoir Characterization, Production Geology, from September 1985 to December 1996 and for Integrated Pilot Reservoir Studies from January 1997 to September 1998. He is Associate Research Director since 1998. His main research interests were studies of active margins in South West Pacific, then of deep sea fans (outcrops and seismic stratigraphy) and since 1985 stratigraphy and sedimentology devoted to reservoir characterization. He has participed in the completion of 14 PhD, 23 *ENSPM* degrees and 5 masters. He has been lecturer at *AAPG*, *SEG*, *ENSPM* and *ENSPM-FI* for seminars since 1978, in French and foreign universities and for foreign companies. He is member of the *Scientific Committee of Geodiversitas* and has been *Associate Editor of Bulletin de la société géologique de France* from 1997. Member of the *Scientific Committee of the Doctoral School of University of Rennes.*

AWARDS

French Academy of Sciences: J. Labbe prize; French Geological Society: L. Bertrand prize; Trophee *CEPM-COPREP*.