3D Geological Object Recognition in High-Resolution Seismic Data

A Case Study from a Palaeocene Fluvio-Estuarine Reservoir in Suriname

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof. dr. ir. J.T Fokkema,  
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op dinsdag 3 Oktober 2006 om 10:00 uur

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This research was financed by Netherlands Institute of Applied Geoscience (TNO B&O)

ISBN 90-9021063-6

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To my wife and children
Acknowledgments

I would like to take this opportunity to thank all of the people that in one way or another have helped me during my study at Delft University of Technology.

First of all, I want to thank my supervisors Stefan Luthi and Lucas van Vliet for all the time they have spent with me, and their support and guidance in helping me to accomplish my goals. I also want to express my gratitude to them for allowing me to carry out this research. The freedom and the trust I had were crucial to the successful completion of this PhD project.

I want to thank the Netherlands Institute of Applied Geoscience (TNO B&O) for funding the project, particularly Rob Arts and Martin Peersmann for their guidance in the periodical meeting and discussions about the progress of the research.

I want to thank Staatsolie Maatschappij Suriname N.V. for supplying the data, and for allowing me to publish the information contained in this thesis. I also very much appreciate the invitation to visit Suriname, the company, and the Tambaredjo Oil Field. I am very grateful to the former E&P Manager of Staatsolie Wiekert Visser, for his support, and for sharing his knowledge about the data and field geology. I also appreciate his valuable suggestions and corrections of this manuscript. I want to thank Mark Budding and Gerhard Diephuis, who were involved with Staatsolie, for sharing their knowledge with me.

During my stay at the Department of Geotechnology I was very well received by all of my colleagues and I have made very good friends. This list is quite long, so I wish to collectively thank you all for your support, in particular, my colleagues from the lunch team for teaching me the Dutch language.

Particular gratitude goes to Hilbrand Haverkamp, whose work has contributed to a subchapter in this thesis and Aernout Schram de Jong, who I supervised daily, and with whom I worked alongside. Aernout's work also forms a subchapter of this thesis.

Finally, I want to thank all of my friends that have supported me and did what was for them possible to help me. I have to thank my family, who are not in The Netherlands, for supporting me from a distance and I must thank my wife and three children, but, as yet, I don't know how …
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Summary

The objective of this study is to develop methods for extracting and quantifying sedimentary bodies in 3D high-resolution seismic data. For this purpose, a case study was used for which a seismic data set with an exceptionally high resolution of a few meters was available, the shallow (~ 400 m) Tambaredjo field in Suriname. Additionally, a large number of densely spaced wells was available that allowed validation of the seismic responses.

In the Tambaredjo field, relatively thin Palaeocene sands constitute the main producing horizons. They are interpreted as sand sheets, channel fills, point bars, crevasse splays etc. that were deposited in a mainly fluvial channel belt system that occasionally underwent marine-transgressive influences. Two fairly continuous horizons with distinct acoustic impedance contrasts were used to reduce the data volume and to delimit the study interval, since they bracket the reservoir sands. These are the top-Cretaceous unconformity and a lagoonal carbonate layer known as the “Hardebank”.

A large-scale interactive 3D visualization system with a 3D user interface was used to permit interactive exploration of seismic volumes and to make appropriate choices of the processing methods to be used. Well and surface data were also integrated into the visual analysis. All data combined provided a powerful tool that has improved the interpretation task. System tools were used to make a rough segmentation of the images and to identify main features in the dataset. Data visualization was further enhanced using different image processing tools.

At a large scale, combined analysis of different image processing output volumes provided important information on the overall lithofacies distributions. A number of seismic attribute volumes were used as input for clustering and supervised classification using Artificial Neural Networks. Unsupervised clustering applied to the attribute volumes produced clusters of voxels with similar properties, i.e. attribute values, whereby the best results were reached using the Universal Vector Quantiser applied to the seismic waveform along the Hardebank horizon. The resulting regional segmentation showed a clear ordering into different depositional zones. In order to understand the meaning of these zones, segmentation into lithologies was performed at a finer scale, whereby a supervised classification method was employed at the voxel level. A feed-forward Multi-Layer Perceptron was found to give the best results. Attribute vectors at selected wells provided the training set with well data (wireline logs combined with sidewall core information) providing the control points or “ground truth” lithologies. Output volumes for the targeted T1 sand and T2 sand were obtained, and the shapes of these sand bodies were extracted as discrete volumes. These permitted the characterization of the shape, size and general geometry of these objects.

It was found that many extracted objects showed shapes that could immediately and confidently be interpreted as channel fills, crevasse splays, or point bars, indicating the mostly fluvial nature of these deposits. However, subtle tectonic deformation of the layers, which generally dip gently northward from the Guyana shield towards the Atlantic Ocean, significantly perturbed the image segmentation task. Particularly folding and small-scale normal faulting often prevented full tracking and extraction of complete sand bodies – although it was recognized that erosion was significant throughout the Palaeocene sequence. It was therefore decided to create a new seismic data volume wherein these deformations are reversed. This was achieved by flattening the top-Cretaceous unconformity marker and the “Hardebank” marker simultaneously and interpolating the seismic data in between with a
spline function. The resulting GeoTime volume represents in the vertical axis geological time, although not linearly and only in a first approximation. However, with this representation (using either the reflected amplitude data or the acoustic impedance data) tracking of geological bodies was found to be considerably facilitated.

In order to find appropriate ways of parameterising the extracted geological bodies, the architecture of actual rivers was studied from aerial photographs and satellite images, particularly of meandering river belts. It was found that the rivers’ central path could be modelled using a natural cubic spline through a set of control points along the river. At each point of the spline-generated curve the radius of curvature was calculated. Inspection of the curvature along the river path at the dominant scale showed that pieces of relative constant curvature were connected by inflection points. The curved segments on the other hand have finite radius of curvature and in those regions can be modelled by a circular arc of the calculated radius that fits as accurate as possible to the river’s central path. Such a sparse representation of a river path is a considerably simpler way of describing it than with a voxel-based approach.

Point bars are the primary sedimentary deposit of such recent fluvial systems, and their shape development through time was studied. Accretion of the point bars was found to be adequately described by a sequence of circle segments along the axis of accretion – which does not need to be along a straight line. A simple model was therefore derived that uses two circle segments as the first and last accretion surface. It is generated by a set of four non-contiguous points. The intersection of these two circles creates a crescent that models the point bar geometry. Two different optimization criteria were used to find the optimum fit to actual data. This crescent model has been applied to point bars extracted from the seismic data set and formed the basis for stochastic modelling of similar reservoirs. From alignment of point bars the trend of the accretion axis can be determined, and from the average of the normal to all accretion axes the average drainage direction of the fluvial belt system can be determined.

All properties combined yielded a quantitative description of a river’s architecture and allowed a comparison of ancient and modern river systems. These parameters can be used for stochastic modelling of similar subsurface system, but obviously a much larger data base will have to be developed for a more universal application. From comparison with well data, the petrophysical properties for the different types of objects are obtained and can also be used for reservoir modelling purposes.
Samenvatting

Dit onderzoek heeft als doel technieken te ontwikkelen waarmee sedimentlichamen in zeer gedetailleerde 3D seismische opnames kunnen worden waargenomen en gekwantificeerd. Voor het onderzoek is gebruik gemaakt van een seismisch gegevensbestand met een buitengewoon hoog oplossend vermogen van slechts een paar meter; namelijk het ondiep gelegen (~ 400 m) Tambaredjo veld in Suriname. In dit veld is bovendien een groot aantal putten dicht bij elkaar geboord, waarmee de seismische gegevens kunnen worden onderbouwd.

De belangrijkste producerende reservoirs in the Tambaredjo veld zijn relatief dunne Paleocene zanden. Men denkt dat deze zanden zijn afgezet als plaatvormige zandlichamen, geulopvullingen, kronkelwaarden, crevassecomplexen e.d., afgezet in een rivierstelsel dat voornamelijk uit geulen bestaat, en dat zo u en dan door een mariene transgressie werd beïnvloed. Teneinde de grote hoeveelheid gegevens hanteerbaar te maken en het onderzoeksinterval af te bakenen, hebben we twee tamelijk continue niveaus met duidelijk herkenbare akoestische impedantie contrasten gebruikt. Deze niveaus, de discordantie aan de top van het Krijt en een Paleocene lagunaire kalklaag, die bekend staat als de “Hardebank”, begrenzen namelijk de reservoir zanden.

Er is gebruikt gemaakt van een grootschalig interactief 3D visualisatie systeem met een 3D gebruikersinterface zodat seismische volumes interactief konden worden bekeken en de juiste bewerkingstechnieken konden worden gekozen. Ook putgegevens en oppervlaktegegevens werden geïntegreerd in de visuele analyse. Alle gegevens tezamen vormen een krachtig stuk gereedschap, waarmee de seismische interpretatie aanzienlijk kon worden verbeterd. Standaard systeemopties zijn gebruikt om de seismische beelden grof onder te verdelen en de voornaamste elementen in het seismische bestand te onderscheiden. De visualisatie van de gegevens is verder verbeterd met verschillende beeldbewerkingstechnieken.

Op een grotere schaal leverde de gecombineerde analyse van de resultaten van verschillende beeldbewerkingen belangrijke informatie op over de globale verspreiding van de verschillende gesteentesoorten. Een aantal seismische attribuutvolumes is gebruikt als input voor clustering en gecontroleerde rangschikking met behulp van Artificial Neural Networks. Als we vrije clustering toepassen op de attribuutvolumes kregen we clusters van voxels met gelijksoortige eigenschappen, b.v. attribuutwaarden. De beste resultaten zijn verkregen toen de “Universele Vector Quanta Omzetter” werd toegepast op de seismische golfvorm langs het Hardebankniveau. De regionale zonering die daaruit voortkwam vertoont een duidelijke indeling in diverse afzettingszones. Om te begrijpen wat deze zonering betekent werd een kleinschaliger verdeling in gesteentesoorten gemaakt, waarbij een gecontroleerde indelingstechniek op voxel niveau werd gebruikt. Een vooruitkoppellende “Meer-Laags Perceptron” bleek de beste resultaten op te leveren. Als oefenbestand kozen we attribuutvectors bij speciaal geselecteerde putten waarvan putgegevens (petrofysische meetgegevens in combinatie met boorgatwandmonster) als controlepunten beschikbaar waren ofwel “fundamenteel juiste” gesteentesoorten. Dit leverde outputvolumes op voor die bepaalde zanden, en de vormen van die zandlichamen werden geselecteerd als afzonderlijke volumes. Deze volumes maakten een typering mogelijk van de vorm, afmeting en algemene configuratie van deze objecten.

Het bleek dat veel van de geselecteerde objecten een vorm vertoonden die met grote zekerheid en onmiskenbaar kon worden geïnterpreteerd als geulopvulling, crevassecomplex,
of kronkelwaard, hetgeen bevestigt dat het hier om rivierafzettingen gaat. Een lichte tektonische deformatie van de lagen, die over het algemeen flauw naar het noorden hellen, van het Guyana Schild naar de Atlantische Oceaan, bemoeilijkt echter de beeldopsplitsing. Vooral plooien en kleinschalige afwijkingsbreuken maken het vaak onmogelijk complete zandlichamen volledig te volgen en te selecteren, al beseffen we natuurlijk wel dat in het hele Paleocène laagpakket een aantal erosievlekken voorkomt. We besloten daarom een nieuw seismisch gegevensbestand te creëren waarin deze vervormingen ongedaan waren gemaakt. Dit werd bereikt door de markers, de discordantie aan de top van het Krijt en de “Hardebank”, beiden tegelijk vlak te trekken en de seismische gegevens daartussen te interpoleren met een spline functie. Het resultaat van deze bewerking, het zogenaamde “GeoTime” volume, vertegenwoordigt langs de verticale benadering is. Maar deze manier van voorstellen (gebruik makend van ofwel de reflectie amplitude gegevens ofwel de akoestische impedantie gegevens) vereenvoudigt het identificeren van geologische lichamen aanzienlijk.

Teneinde op een goede manier beschrijvende parameters te formuleren voor de aldus geselecteerde geologische lichamen, hebben we de opbouw van recente rivierstelsels bestudeerd op luchtfoto’s en satellietbeelden, vooral van meanderende rivierstelsels. Het bleek dat het meest waarschijnlijke tracé van de rivier gemodelleerd kon worden met behulp van een derdemachts spline door een aantal controlepunten langs de rivierloop. Op elk punt van de met de spline functie verkregen curve werd de kromtestraal berekend. Toen we de meest voorkomende kromte langs de rivierloop bekeken bleek dat stukken met een tamelijke constante kromte verbonden zijn door buigpunten. De gekromde stukken hebben echter een eindige kromtestraal en kunnen worden gemodelleerd door cirkelbogen met de berekende straal die het centrale riviertracé het dichtst benadert. Dit is een veel eenvoudiger voorstelling van een rivierloop dan een beschrijving door middel van een op voxels gebaseerde benadering.

Kronkelwaarden vormen de voornaamste afzettingen in recente riviersystemen van dit type en we hebben de ontwikkeling van de vorm van kronkelwaarden door de tijd bestudeerd. De aangroei van kronkelwaarden bleek te kunnen worden beschreven door een aantal cirkelsegmenten langs de aangroei-as, maar die aangroei-as hoeft geen rechte lijn te zijn. We hebben daarom een eenvoudig model afgeleid waarin de eerste en laatste aangroei-oppervlaktes vertegenwoordigd zijn door twee cirkelsegmenten. Dit model kan worden gegenereerd uit vier niet-aaneensluitende punten. De doorsnede van twee cirkels heeft een halvemaanvorm, een perfect model van de vorm van een kronkelwaard. Er zijn twee verschillende optimaliseringcriteria gebruikt om de werkelijkheid het best te benaderen. We hebben dit halvemaanvormige model toegepast op kronkelwaarden die we hadden geselecteerd uit het seismische gegevensbestand en dit vormde de basis voor het stochastisch modelleren van vergelijkbare reservoirs. Uit het tracé van de kronkelwaarden kon de richting van de aangroei-as worden bepaald en uit het gemiddelde van de loodlijn op alle aangroei-assen de gemiddelde stroomrichting van het rivierstelsel.

Al deze eigenschappen bij elkaar leverde een kwantitatieve beschrijving van de opbouw van een rivier op en maakte het mogelijk oude en moderne rivierstelsels te vergelijken. Deze parameters kunnen worden gebruikt om dit soort rivierstelsels in de ondergrond te modelleren, maar uiteraard dient een veel groter gegevensbestand te worden opgebouwd voordat de techniek algemeen toepasbaar is. Vergelijking met putgegevens levert de etofysische eigenschappen van verschillende soorten geologische objecten en die kunnen dan weer worden gebruikt om reservoirs te modelleren.
1. Introduction

The growth of the global economy, the standard of living and the world population, especially in the emerging countries, causes an increasing worldwide demand for oil and gas. Particularly in developing countries, the upstream exploration and production (E&P) industry has launched a set of initiatives to optimize the search for and production of conventional hydrocarbons. The technology which has always been at the forefront of the industry's major achievements throughout its history, will assume an even more prominent role in the 21st century. A decade ago many oil company efforts could be characterized as one-dimensional, oriented exclusively toward solving specific problems. Interrelationships and interdependencies among various technologies were often not examined or exploited. Today, the oil industry is focusing, to a much greater extent, on a multi-dimensional, process-based approach that recognizes the advantages of merging a variety of technologies and disciplines. This new approach involves scientists and engineers with different backgrounds, expertise and international experience. Technologies and expertise do not have to be expensive or complex, but individually and collectively they must incorporate an integrated, best practices approach. That means integration of data, interpretations, models, simulations and the evaluation of development and production.

In the last years three-dimensional (3D) seismic reservoir imaging has been adopted by the industry not only to play an important role as starting point for building reservoir models, but also in combining and merging datasets from various modalities and to validate methods. Since the first 2D and later 3D seismic survey, new fields of investigations were developed. The investigations have not always been product-oriented, but have also been carried out to gain new insights in geological processes and in understanding geological data.

The interpretation of seismic data has changed since the first 3D survey, always progressing with the aid of new technology improvements. High resolution seismic (HRS) datasets still have a lot of potential to be exploited. Geological features of a size close to the seismic resolution are very difficult to recognize. This challenges geologists and seismic interpreters to fill the existing gaps between seismic and reservoir models. Image processing techniques can be used to enhance those subtle image features in the data, and provide the basis for the automations of many interpretation tasks. Immersive 3D visualization also provides a substantial improvement in the interpretation process, since it allows the extraction of more information from seismic images and seismic images provides companies with quantitative
tools to improve production, to estimate reserves and in general to better understand reservoir characteristics.

Fluvial sedimentary systems, for example, are of great interest for production geologists because they constitute potential hydrocarbon reservoirs. However, these systems are among the most complex and heterogeneous ones encountered in the subsurface. Geological bodies of interest can have sizes close to, or below the resolution of the seismic dataset, which means that only some of them can be visible on 3D seismic images.

In the present work, an immersive visualization tool with a 3D user interface and interactive colour manipulation was used to perform an analysis of a high-resolution seismic dataset from a mostly fluvial oil reservoir.

The general objective of this thesis is to find the geological patterns, extract them with suitable techniques and understand their relationship for gaining insights into the sedimentary environment. In order to solve this complex task, modern analogues have been studied and the knowledge thus gained was translated into software tools that can be used to achieve the objectives of this thesis.

A suite of different tools to identify and classify sedimentary layers, but also to delimit their boundaries and isolate individual geological objects was explored. Extracted geological objects were parameterized using a minimum number of parameters. The parameters can subsequently be used for predictions and extrapolations beyond the areas of study.

1.1. Dataset: Tambaredjo Oil Field, Suriname

In order to fulfil the objectives of this research a fluvial sedimentary system was studied in detail. The dataset comes from a fluvio-estuarine reservoir in Suriname (Guyana coast, South America). The field is located in a marshy area in the coastal plain of Suriname approximately 45 km west of Paramaribo as shown on the map in figure 1.1. The Tambaredjo Oil Field is the first oil-producing field in Suriname and is operated by the State Oil Company “Staatsolie Maatschappij Suriname N.V.”. Its production is above 10,000 barrels per day of heavy crude oil with intermediate naphtenic composition, low sulphur and low metal contents.

The oil is produced from Palaeocene unconsolidated sands in the lower part of Saramacca Formation. The depositional environments range from fluvial to deltaic and/or estuarine. The Palaeocene sands are subdivided into a basal T1 sand and upper T2 sand. The T1 sands are deposited as channel-fill sands and sand sheets by low sinuosity channels. The geometry of T1 sand bodies in the Southern part of the field is mainly controlled by the underlying erosion surface that marks the top of the Cretaceous. The T2 sands range from channels and point bars to estuarine fills and crevasse splays.

In 2001, a 3D high-resolution seismic dataset was acquired. The dataset was recorded at a very high frequency over approximately 83 km² with a bin size of 6.25 meters in both lateral directions (see rectangle in figure 1.2). Because of the high recorded frequency, the vertical resolution ranges from 2.5 to 4 meters. The shallow location of the reservoir makes drilling easy and a large amount of wells is available. The geological framework is further described in detail in chapter 2, where background information about the geology of Suriname and South America is included together with the characteristics of the acquired seismic survey.
Introduction

Figure 1.1. Map of petroleum occurrences in the Guyana basin (Courtesy of Staatsolie Maatschappij Suriname N.V.).

Figure 1.2. Satellite image of the northern part of Suriname, the enclosed area (white) marks the Tambaredjo Oil Field (Courtesy of Staatsolie Maatschappij Suriname N.V.).
1.2. Analysis of seismic data

The special characteristics of the seismic images, together with the complexity of the subsurface geology, require a careful analysis and appropriate tools. High-resolution three-dimensional seismic data can provide unique insights into sedimentary systems. They will never exhibit the same amount of detail as outcrops, but their three-dimensional nature adds an element that is difficult to obtain from outcrops.

Modern image processing applies 3D operators to a 3D data set, rather than processing a stack of 2D images sequentially by 2D operators. Three-dimensional methods preserve the true three-dimensional integrity of the data set including all topological and connectivity relations. Interpretation work of 3D images on a conventional computer system (PC or workstation) is cumbersome and computationally expensive. Immersive visualization technology interacts with the user through a 3D user interface and facilitates interactive image manipulation. This is often referred to as “virtual reality”. It reduces the time and effort substantially and brings new insights in the seismic interpretation process. The immersion reached with such a system and the enhanced visualization capability, is found to be a substantial help for understanding complex geological systems.

The visual analysis of the Tambaredjo seismic data was done using the 3D visualization facility available at the Department of Geotechnology at the Delft University of Technology. The details of this 3D visualization system are described in the appendix A. In chapter 3, three main seismic facies identified are presented: two high-acoustic contrast layers that were used as delimiters of the study interval, and the sands. The methods developed to improve image visualization and segmentation are also described there.

1.3. Classification and object extraction

The complexity of the subsurface geology as a result of depositional processes, erosion and tectonic movements is clearly seen in the 3D seismic volumes. The seismic facies although at first sight chaotic, upon closer inspection reveal order and regular patterns can be found. A specific objective of the thesis was the classification of the seismic images into lithologies.

In chapter 4, a classification process at the voxel level is described. The use of a neural networks to cluster seismic data is explained, the clustering results and knowledge of the lithologies present are used to classify the seismic data by means of a supervised network trained on a separate data set for which the "ground truth" or validation is obtained from cores and well logs. The neural network output consists of probability cubes that allow assigning lithofacies to each individual voxel with a certain range of probability. A detailed quality control was made, with control points at the well locations.

Chapter 5 illustrates how the voxels are grouped and analyzed as image segments. These segments are classified at object level based on patterns and geometries that can be recognized from objects in the different output volumes. In order to better define the object boundary and to correct the deformations caused by post-depositional processes, such as erosion and tectonic movements, a newly developed method is presented. This method uses geological markers to compute a seismic volume in which the vertical axis corresponds
Introduction

This volume, termed GeoTime cube, is no longer affected by post-depositional deformations, a feature that greatly facilitates the extraction and correct parameterization of sedimentary bodies.

1.4. Parameterization of common geological objects in meander belt systems

Parameterization of extracted objects constitutes also an important objective of this research project. The methodology for object parameterization helps to understand and predict occurrences of specific geological objects. In chapter 6, the methods developed for the parameterization of the most common features found in the data set, which in essence is a channel belt system, are described. Quantitative description of these objects with a minimum number of parameters has several advantages, for example to store them, to interchange data in real time with other applications and/or workplaces and, most importantly, to extract the necessary information for predicting further occurrences.

The methods to quantify ancient bodies found in the high-resolution seismic dataset use modern analogues to validate the approach. The most basic element to parameterize is the channel path, which is modelled with a natural cubic spline. The paths of meandering rivers are found to show characteristic patterns, notably a relatively constant curvature of each meander loop, and a characteristic spacing of the meander loops. The main depositional products of these rivers are point bars, which are caused by lateral accretion of sand on the inner banks of the evolving meander loops. Their shapes can be approximated by two intersecting circle segments, representing the initial and the final position of the meander loop. The axis of the circle centres corresponds to the direction of accretion, and the normals to these axes can be used to describe the general direction of the meander belt. Knowing these parameters from a limited area can, therefore, be used to stochastically model the continuation of the meander belt in the up- and down-stream direction.

The last chapter is devoted to a discussion of the contribution made to the methods for the (visual) analysis of the high resolution seismic dataset, the methodology for segmentation and classification of seismic images and the new methods developed for the parameterization of the extracted geological bodies.
2. Dataset: The Tambaredjo Oil Field in Suriname, South America

2.1. Introduction

The high-resolution seismic (HRS) data set used for the research into seismic volume visualisation is from the Tambaredjo Oil Field in Suriname (Guyana Coast, South America), operated by Staatsolie Maatschappij Suriname N.V. The seismic survey was acquired in 2001 and contains 1666 in-lines and 1284 cross-lines with 6.25 m spacing, covering an area of 83 km² (Fig. 2.1). The reservoir is in the Palaeocene fluvio-estuarine Saramacca Formation at a depth of 300-400 m and contains heavy oil. The field is perforated with grid drilling at a spacing of 200 m. The well log data of these wells were used for validation of the seismic modelling output. The HRS data set is pre-stack migrated and processed with a focus on obtaining optimal data at the reservoir interval.

2.2. Geological framework

The Guyana Shield (Fig. 2.2) is a crystalline Proterozoic basement that underlies about 80% of Suriname’s onshore territory. The Shield is bordered to the north by the Guyana sedimentary basin. This basin formed in the Late Jurassic – Early Cretaceous with the opening of the South Atlantic Ocean, as the South American and African plates began to drift apart (Fig. 2.3). After an initial rifting phase the basin gradually subsided in a passive trailing continental margin setting (Wong, 1994). The opening of the South Atlantic Ocean created a transform margin in the northern Demerara Plateau (offshore Guyana, Fig. 2.2) and a pull-apart basin in the deeper part of the Guyana Basin (Sanchez, 2001). Sedimentation in Guyana Basin shows a gradual southward onlap onto the Guyana Shield. Clastic sediment to the basin was supplied by large rivers draining the Guyana Shield. The basin fill ranges from Berriasian (Early Cretaceous) to Pliocene age. Largest thickness of the sediment wedge (in excess of 8700 m) is on the continental shelf north of present-day Suriname (Fig. 2.5). In the coastal plain of onshore Suriname the thickness decreases from nearly 2000 m in the west to 200 m in the east. From south to north sedimentation took place in a succession of continental to marine depositional environments (Fig. 2.5): fluvial to coastal to shallow marine and deep marine.
Figure 2.1. Simplified geological map of Suriname, where is pinpointed the location of the Tambaredjo field, the shape of the field ad the seismic survey are zoomed in on the right (Courtesy of Staatsolie Maatschappij Suriname N.V.).

2.2.1. Geology of the Tambaredjo Oil Field

The regional geology of the Suriname coastal area has been described in detail by IJzerman (1931), Noorthoorn van de Kruijff (1970), Hanou (1981), Wong (1976, 1986, 1994, 1998), Bergval (1984), Jharap (1984). The deposits in the coastal area are of Late Cretaceous (Nickerie Formation) to Holocene (Coronie Formation) age and form part of the Corantijn Group (Wong, 1994). The Tambaredjo oil reservoir is in the Palaeocene-Eocene Saramacca Formation (Fig. 2.4). The Saramacca Formation is 120-150 m thick and unconformably overlies the Nickerie Formation. In the Tambaredjo area, the Coesewijne Formation unconformable overlies the Saramacca Formation. Both the upper and the lower boundary of the Saramacca Formation are type-1 sequence boundaries as defined by Van Wagoner et al. (1988) and represent a relative fall in sea level below the position of the shelf break. The formation boundaries form good seismic markers and can easily be recognized on wireline logs by the distinct characteristic on the bulk density log (see rightmost log in figure 2.4): the
Tertiary sediments are unconsolidated and have a significantly lower density than the compact and strongly kaolinized Cretaceous sediments. The sands in the sedimentary section above the Saramacca Formation have densities that are greater than those of the Saramacca sediments. The Saramacca Formation is characterized by a regular alternation of relatively thick (up to 50 m) more or less kaolinitic sands with kaolinitic clays (Wong, 1986). Locally very fine gravels may be intercalated. The sands consists of translucent quartz grains, which are very fine to very coarse, poorly sorted to well sorted and sub-angular to surrounded. Occasionally, shell fragments are found in the sands indicative for brackish or marine influence.

![Figure 2.2. Ocean floor architecture derived from satellite gravity data (Courtesy of Staatsolie Maatschappij Suriname N.V.). The east-west lineaments show the drift paths of the African and South American Plates away from the Mid-Atlantic Ridge.](image)

The sedimentary history of the Saramacca Formation is conditioned by successive periods of relative base level changes. The base of the Formation is a sharp truncation surface at the top of the Cretaceous deposits. The surface features localized incised fluvial valleys and marks a major relative base level fall and associated basinward shift of facies. The change from a fluvio-deltaic to a shallow marine environment of deposition marks the transgressive response to a relative base level rise in the Early Palaeocene. During a next relative base level fall at the end of Palaeocene a continental environment returned to the area of the Tambaredjo field. A rapid transgression took place at the beginning of the Eocene and the area became the realm of deltaic deposition. In the subsequent stable base level progradation of fluvial sands over the deltaic environment caused a depositional regressive succession. Following deposition of fluvial sands, another marine transgression caused deposition of marine shale in sharp contact.
with the fluvial sands. Additional depositional cycles may have taken place in the late Eocene, but erosion during the Oligocene and Miocene removed this part of the stratigraphy (Wong, 1989; van Santen, 1991).

Figure 2.3. Tectonic evolution of the Guyana basin (Courtesy of Staatsolie Maatschappij Suriname N.V.).

2.2.2. Reservoir Geology

Located in a marshy area in the coastal plain approximately 45 km West of Paramaribo, the Tambaredjo Oil Field was the first producing oil field in Suriname (Figs. 2.3 and 2.4). Oil production in the Tambaredjo field is from the T-unit, a Palaeocene member of this Formation. Staatsolie reports that a mature source rock of Cenomanian-Turonian age was penetrated by a well located offshore Suriname, approximately 150 km Northward of the present shoreline. The absence of oleananes, Tertiary resin indicators in the Saramacca crude oil, is taken as evidence for a Cretaceous or Jurassic age of the source rock.

Unconformities may have acted as main migration paths for the updip oil migration into higher lying sediments (Fig. 2.5). Regional impermeable shale beds prevented vertical migration, while onshore pinchouts of the permeable beds prevented further lateral migration, trapping the oil in the coastal area at shallow depths. The trap style is therefore considered a combination of pinch outs and faults in the southwest, and probably by faults in the southeast.

The Tambaredjo Oil Field contains 900 million barrels of medium heavy (15°-17° API) oil in place. Recoverable reserves are estimated at 167 million barrels (Staatsolie Maatschappij Suriname N.V.). The oil gravity in the onshore area is around 16° API and gradually increases to the North. Nearshore, the gravity is 22° API while in the deep offshore Abary well the gravity was found to be 34.7° API. The oil is of kerogen type II (Hold, 2000). Biodegradation of the oil due to long-range migration from the Cenomanian-Turonian source kitchen to the South is thought to be the main cause of these gravity differences.
Figure 2.4. Well penetration: type logs, and hydrocarbon occurrences in the onshore area of Suriname (Courtesy of Staatsolie Maatschappij Suriname N.V.).
The oil-bearing sands of the Tambaredjo reservoir are in the T-unit of the Palaeocene part of the Saramacca Formation (Fig. 2.4). The reservoir sands have a clay seal. The reservoir sands are encountered at an average depth of about 350 m in the southern part of the field and have a gentle monoclinal dip to the North. In the south of the field the lower contact of the T-unit is formed by the Cretaceous-Tertiary truncation surface. In the North, the T-unit is underlain by a Palaeocene water-bearing unconsolidated sand, the U-sand. In the onshore and nearshore area, this sand is believed to be a deltaic deposit. The top of the U-sand is assumed to be an eroded surface of a clay layer (Wong, 1998). Very shallow dips prevail throughout: the basement dip averages two degrees, the Upper Cretaceous unconformity slightly over one degree, and the Mid-Miocene unconformity only a fraction of one degree.

The clay-rich top of the T-unit is overlain by the S-sand (Fig. 2.4). Deposition of sand and shale in the latter unit occurred during the shift from marine to transitional marine environments, suggesting a progradational succession during constant relative sea level.

Except for the field limits to the South and Southwest, the full extent of the Tambaredjo field has not been determined yet. To the South, sand pinch-out accounts for the field’s boundary. The south-western flank of the Tambaredjo reservoir is abruptly bordered by water-bearing T-sands. The reason for this abrupt change is not yet known. The northwestern and eastern boundaries have not been determined yet by drilling but are assumed to be faults.

Correlation between onshore and nearshore wells showed continuity of the T-unit well into the nearshore area, where it seems to be oil-bearing as well, and thus qualifies as an outstep prospect to the Tambaredjo field.
Figure 2.6. Sketch of the Tambaredjo Oil Field. Highlighted are the developed areas and some stratigraphic test wells. Situation in the year 2001 (courtesy Staatsolie). These wells are in fact appraisal wells and as such extend the grid information coverage of the field beyond the production wells, which have been drilled in scheme with a well spacing of 200m. The oil-water contact (OWC) at T1 level is located in the northern part of the field and is indicated by the dashed line. Situation in the year 2001 (Courtesy of Staatsolie Maatschappij Suriname N.V.).

Based on the overall geological picture it seems plausible that a similar depositional system as the T-sand in the Tambaredjo field could exist in other parts of the coastal area. From the net sand contour map and the trends derived thereof, the eastern and north-western flank of Tambaredjo appear to represent a significant onshore potential. This is the case of the Calcutta field (see figure 1.1), which is currently at exploration and appraisal stage. A few wells are on production since 2003 (Staatsolie annual reports available at http://www.staatsolie.com).

In the early exploration and development stage of the field it was believed that the T-sand was deposited in a sheet-like manner as a uniformly thick sand body (Hanou, 1981). As development proceeded, it became clear that the T-sand is not a massive, uniformly distributed sand body but that it is composed of several laterally discontinuous and vertically stacked fluvial sand bodies (Dronkert et al., 1991). The thickness of the oil-bearing sands varies up to approximately 15 m and the sand distribution is very irregular. In some wells, the T-sand is totally absent.
With well-spacing distances of 200 m, reservoir quality is found to change considerably from well to well. In many cases, good producers are found immediately adjacent to very poor producers. In such a complex labyrinth-type reservoir it is of utmost importance to obtain a detailed picture of the geometry and depositional nature of the T-sands in order to minimize the dry-hole percentage and optimise the drill-site prediction. Hence, several reservoir studies were carried out in the early 1990s (van Santen, 1991; Dronkert, 1991; Nandlal, 1993).

Figure 2.7. Idealized sequence stratigraphy for the Tambaredjo area. The base of the T-unit is a sequence boundary that truncates the underlying Cretaceous deposits. The overlying fluvial T1 sands formed during the early TST as incised valley fill. Progressive drowning of the system resulted in a gradual change to late TST fine-grained tidal flat deposits and estuarine / tidal channels sands (T2) and a cemented maximum flooding surface (Hardebank).

The T-unit is subdivided into two major units, the T1 and T2 units (van Santen, 1991). The lower reservoir, T1, is a basal sand-prone interval, overlain by an inhomogeneous clay unit; the upper reservoir, T2, is overlain by a sealing clay unit. The latter consists of a variable number of clay beds, lignites, silt and (mostly water-bearing) sands. In the North, a regional thin and tight calcareous layer is present at, or near the base of the sealing clay, the so-called “Hardebank” (Dutch for hard layer). This layer (in the following always referred as Hardebank) directly overlies the reservoir sands in the Sarah-Maria area (Fig. 2.6) and pinches out towards the South. In the northern part of the field, a clay layer is also present between the reservoir sands and the calcareous zone. The Hardebank constitutes a very important feature in the dataset because it is imaged exceptionally well. It is addressed several times in this document and several images of it are shown below and in the next chapters.

The thickest development of T1 sand is associated to palaeo-valley fills on the Top Cretaceous unconformity surface. The T1 sands are described as moderately- to well-sorted,
medium- to coarse-grained sands (Staatsolie internal documents). The basal portions are often poorly sorted and coarse-grained to conglomeratic. The T1 and T2 sands show a fining upward sequence. The T2 sands are relatively finer-grained and clay-rich. Their average permeability is less than that of the T1 sands; ranges of values for permeability obtained from logs are presented in table 2.1. Often, only the lower part of the T2 sand has favourable reservoir characteristics. T1 and T2 constitute the most important features in the field from the production point of view, and they constitute the main targets for object quantification in this study.

The T-unit is interpreted as a progressively drowning fluvial to estuarine depositional system (Nandlal & Mwakipesile-Arnon, 1998; Fig. 2.7). The T1 sands are fluvial deposits of the early transgressive systems tract (early TST) that filled the incised valleys formed during the preceding relative base level fall. Drowning of the T1 fluvial system resulted in the deposition of late TST fine-grained tidal flat deposits and sand-filled tidal channels and estuarine deposits. The Hardebank may be regarded as the maximum flooding surface.

2.3. Field development

2.3.1. Introduction

The State Oil Company “Staatsolie Maatschappij Surinamee N.V.” was established by the government of Suriname in 1980, and oil exploration on the Tambaredjo area started in 1981 with three exploration wells. The early production process was very basic but adapted to local conditions. The produced oil is a heavy intermediate naphtenic crude with low sulphur and low metal contents.

![Figure 2.8. Production history until year 2004 (Staatsolie document).](image-url)
Nowadays, Staatsolie Maatschappij Suriname N.V., together with mining enterprises Suralco and Billington, is one of the most important companies in Suriname with oil production of over 10,000 barrels per day (Staatsolie annual report 2004). The Tambaredjo Oil Field has about 900 million barrels of STOIIP (stock tank oil initially in place) of which about 160 million barrels have been booked as reserves. The historical production is presented in figure 2.8.

Since April 2003, Staatsolie has also started the production in the Calcutta field next to Tambaredjo. This reservoir is of upper Eocene age and the recoverable reserves are estimated to be at least 16 MMBBLS (Staatsolie annual report 2004). The exploration and appraisal efforts in this field are still ongoing. The basic data of the Tambaredjo oil reservoir are summarised in table 2.1.

The oil is pumped to the surface with electrical progressive cavity pumps and then fed into production lines that are gathered and brought to a central processing plant. From there, the oil is transported through a pipeline to Paramaribo, the capital of Suriname (Figure 2.9).

Table 2.1. Summary of the main characteristics of the reservoir in the Tambaredjo field (Staatsolie document and personal communication with W. Visser)

<table>
<thead>
<tr>
<th>Geological Age</th>
<th>Palaeocene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir Rock</td>
<td>T Units: unconsolidated, clean, and shaley sand.</td>
</tr>
<tr>
<td>Reservoir Depth [m]</td>
<td>260 – 460</td>
</tr>
<tr>
<td>Reservoir Pressure [psi]</td>
<td>390 – 500</td>
</tr>
<tr>
<td>Formation thickness [m]</td>
<td>5-45</td>
</tr>
<tr>
<td>Maximum Oil sand thickness [m]</td>
<td>15</td>
</tr>
<tr>
<td>Net Sand Thickness [m]</td>
<td>0 – 15</td>
</tr>
<tr>
<td>Drive mechanism</td>
<td>Mainly compaction.</td>
</tr>
<tr>
<td>Trapping</td>
<td>Reservoir is gently dipping northwardly. Trapping in the South West: probably combination of pinch outs and faults; and in the South East probably by faults.</td>
</tr>
<tr>
<td>Reservoir boundaries</td>
<td>Oil and water contact is not clear. Oil Down To Contacts encountered in depths 400-460 m in the northern wells. Eastern and western boundaries unknown.</td>
</tr>
<tr>
<td>Depositional Environment</td>
<td>Valley fill, lower coastal plain.</td>
</tr>
<tr>
<td>Porosity [%]</td>
<td>35-42 average 38</td>
</tr>
<tr>
<td>Water Saturation [%]</td>
<td>7 - 50</td>
</tr>
<tr>
<td>Permeability [D]</td>
<td>0.500 – 40</td>
</tr>
<tr>
<td>Oil gravity [API]</td>
<td>16</td>
</tr>
<tr>
<td>Oil viscosity [cp]</td>
<td>500 – 1500</td>
</tr>
<tr>
<td>GOR [sccf]</td>
<td>0-40</td>
</tr>
<tr>
<td>Reserves + size (proven)</td>
<td>900 MMSTB 147 km²</td>
</tr>
<tr>
<td>Recoverable reserves</td>
<td>16 MBBBLS</td>
</tr>
</tbody>
</table>
2.3.2. Development wells

The shallow depth of the reservoir makes drilling relatively easy and fast (figure 2.10). Until now around 1000 wells have been drilled with an average time from spudding to completion of one week. An example of the field development put in practice is shown in figure 2.11. The grid drilling uses a 200 meter well spacing, and the drilling program proceeds in clusters.

Figure 2.9. Field pipelines that transport the oil to Paramaribo, the capital of Suriname (Courtesy of Staatsolie Maatschappij Suriname N.V.).

Figure 2.10. Production drilling in the Tambaredjo Oil Field (Courtesy of Staatsolie Maatschappij Suriname N.V.).
In each well, a standard logging suite is recorded, and generally sidewall core samples are taken because full coring is difficult due to the uncompacted nature of the sands. Only a few meters of full core material were retrieved and described, (Staatsolie document, see figure 2.12 for an example).

Figure 2.12. Example of an unconsolidated core from oil-bearing sand interval (Courtesy of Staatsolie Maatschappij Suriname N.V.).

2.4. Well logs

The standard logging suite includes calliper, gamma ray, spontaneous potential, neutron porosity, bulk density, sonic velocity and several resistivity logs.

The sonic velocity log is used to convert the seismic data from time to depth in order to calibrate the seismic to the wells. Unfortunately, there have been problems with the acquisition of high-quality sonic wireline logs. Several sonic logs are believed to be unreliable. They do not always depth-match the bulk density logs and sometimes have an unrealistic trend of increasing sonic transit time with increasing depth, where a decrease in sonic velocity is expected.
An example of a qualitative, manual way of identifying the lithological sequence from well logs is shown in well 3T07 in figure 2.13. From top to bottom the lithologies on well from young to older: At about 1100 ft (~335 m) the top of the T-unit is seen (denoted by 1 in figure 2.13). A sudden increase in density (denoted by 2 in figure 2.13) marks the Hardebank, which in other wells can also appear as two thinner layers. An increase in the gamma ray and a decrease in the resistivity indicate a claystone layer (denoted by 3 in figure 2.13).

Subsequently, a resistivity increase and a neutron porosity and gamma ray decrease (denoted by 4 in figure 2.13) indicate that the first reservoir sand unit, the T2, is entered. This T2 unit can be a single sand layer or a number of alternating smaller sand layers separated by claystones.

In some wells drilled in the study area there is a lignite layer present between the T2 and the T1 reservoir sand (5 in figure 2.13). This lignite layer is characterized by extremely high gamma ray values due to the presence of radioactive elements and by a very low density. A slow decrease in radioactivity and a rapid increase in density (denoted by 6 in figure 2.13)
indicate a transition to another claystone, which, generally, has high kaolinite content. A resistivity increase and a gamma ray decrease (denoted by 7 in figure 2.13) mark the beginning of the second reservoir sand unit, the T1 sand. This unit is usually massive with high resistivities ($>10$ Ohms) indicating the presence of oil. Below it, a sharp density and gamma ray increase and a resistivity decrease (denoted by 8 in figure 2.13) indicate the base of the T-unit, which is identical to the Top Cretaceous unconformity.

In the sidewall core samples retrieved from wells the sands within the T-unit have the following composition: quartz is the dominant mineral, and pyrite, feldspar and calcite are minor minerals. The shales are composed of kaolinite (usually the dominant mineral), smectite, chlorite and illite (Staatsolie internal documents).

### 2.5. Seismic survey

#### 2.5.1. Introduction

In 2000 Staatsolie decided to acquire a high resolution 3D seismic data, with the objective to get an image of the subsurface that would allow improvement of the oil recovery from the reservoir sands, and the acquisition of data to build a subsurface model, that is accurate and detailed enough to significantly impact the Tambaredjo field development planning. The results should lead to improved oil recovery at a lower cost/barrel

Previously, there were no maps for the top and the base of the reservoir sequence. The sand distribution was not understood. It was no concept of fault system. The only development option was grid-drilling (figure 2.11), and the options to improve the recovery were very limited (personal communication with W. Visser). The main parameters of the seismic survey are summarized in table 2.2.

| Table 2.2. Main parameters of the Tambaredjo seismic survey |
|----------------------------------|------------------|
| Survey dimensions               | 10.4 km long and 8 km wide |
| Area                            | 83.2 km$^2$      |
| Vintage                         | 0                |
| Type of receivers used          | hydrophones      |
| Time window                     | 1000 ms          |
| Inline range                    | 3-1666           |
| Crossline range                 | 5-1284           |
| Inline spacing                  | 6.25 m           |
| Crossline spacing               | 6.25 m           |
| Number of traces                | 2128640          |
| Polarity                        | zero phase       |
| Estimated vertical resolution   | 2.5 - 4 m        |

Several tests were carried out by the acquisition company$^1$ together with Staatsolie, including a pilot test in a small area (approximately 4 km$^2$) in the central part of the field. The advice to acquire the Main Survey was positive because the Top Cretaceous could be mapped with good confidence. Top of the T-unit seal could be mapped with good confidence too. Faults

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$^1$ Veritas DGC.
can be mapped with good confidence and the sand distribution within the T-unit can be mapped with reasonable confidence.

![Marshphones](image1.png) ![Hydrophones](image2.png)

**Figure 2.14.** Bandwidth comparison between marshphones and hydrophones. A significant difference in the effective bandwidth is clearly shown (Courtesy of Staatsolie Maatschappij Suriname N.V.).

![Marshphone signal](image3.png) ![Hydrophone signal](image4.png)

**Figure 2.15.** Zero phase wavelets derived from both hydrophones and marshphones for 40g charge of dynamite planted at 6 m depth (Courtesy of Staatsolie Maatschappij Suriname N.V.).

The tests showed among other results that hydrophone records were better than marshphone records in terms of useful bandwidth and thus resolving power (figure 2.14). Figure 2.15 also

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2 Marshphones were used because of the presence of a swamp that covers large part of the field area.
22 shows a comparison of signal quality between the marshphones and the hydrophones for 40 g of dynamite, planted at 6 m depth (Staatsolie document).

An example of the processing of shots is shown in figure 2.16. This image shows a row shot and a single window deconvolution that was run with a 100-900 ms window at zero offset. A two windowed deconvolution was tested, but there wasn’t enough improvement to warrant it, and it is difficult to properly define the two windows without the transition zone being in the zone of interest. Also the windows would have to be spatially variant due to the northerly dips.

![Figure 2.15. Shot record after deconvolution in the left image A and raw shot in the right image B (Courtesy of Staatsolie Maatschappij Suriname N.V.).](image)

The main technical risks were the poor data zones as illustrated in figure 2.16. The heterogeneity of the data is clearly visible in the pilot area at 225 -325 ms.

Finally a 3D seismic dataset was acquired with the parameters listed in table 2.2. The survey was recorded with extremely high resolution and the main objectives mentioned above were fulfilled. Figure 2.17 show a 3D image of the seismic dataset, where are shown three seismic
sections, the top Cretaceous unconformity, and the estimated oil water contact (OWC). The top T unit is also pinpointed.

**Figure 2.16.** An example of poor data zone, where the heterogeneity of the data was an important technical risk (Courtesy of Staatsolie Maatschappij Suriname N.V.).

**Figure 2.17.** 3D seismic survey, which covers large part of the Tambaredjo Oil Field. Interpretation of the top Cretaceous surface and OWC (See colour version of this figure in appendix C).
2.5.2. Wavelet and vertical resolution

There exist several methods and approaches for wavelet extraction from seismic data (Danielson & Karlsson, 1984; Poggiagliolmi & Allred, 1994). The wavelet extracted by Haverkamp (2002) using statistical method and data from a sub-volume of the Tambaredjo dataset is shown in figure 2.18. The dominant frequency calculated in this sub-volume is equal to 125 Hz. Assuming a velocity of approximately 2000 m/s at reservoir level, a wavelength of 16 m can be estimated:

Based on the wavelength (Badley, 1985) an estimation of the theoretical vertical resolution can be made using the approximation $\lambda/4$. The result is a theoretical vertical resolution of 4 m.

![Estimated wavelet of the Tambaredjo seismic survey (Haverkamp, 2002).](image)

**Figure 2.18.** Estimated wavelet of the Tambaredjo seismic survey (Haverkamp, 2002).

2.5.3. Horizon interpretation

A look at the seismic section, depicted in figure 2.19 A, reveals the presence of two reflections close to the reservoir depth. The interpretation of these two main horizons was done by Staatsolie (figure 2.19 B), and the raw interpretation data were supplied to us. After a quality control of the interpretation, a fine tuning was made in order to achieve the quality requirements of this project. Visual analysis of the images and well log information (see figure 2.19 B) reveals that is possible to recognise even less than 3 m thick layers. An estimation of real vertical resolution\(^3\) between 2,5 and 4 m for the target interval (between the Hardebank and top Cretaceous unconformity) is acceptable.

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\(^3\) The vertical resolution estimation is valid only for the study interval between the Hardebank and top Cretaceous unconformity.
The first and oldest horizon highlighted in figure 2.19 (A) is the unconformity at the end of the Cretaceous named “Top Cretaceous” by Staatsolie (see figure 2.17). The second, younger but stronger reflector in seismic terms is the Hardebank, which together with the Top Cretaceous, forms the bottom and the top of the interval of interest. More information about these layers, together with 3D maps and the geological interpretation will be provided in the next chapter. Several faults are visible in the reflectivity images; they can be highlighted with the help of the variance cube.

2.5.4. Variance cube

A measure for the reflection continuity in a seismic image is called variance or coherence. The variance cube calculates at every point in the volume the lateral and vertical dissimilarity of seismic data. Mathematically a function is considered continuous if

\[
\lim_{{x \to x_0}} f(x) = f(x_0) \quad \text{for all } x_0
\]

In order to analyse the variance of the seismic dataset, a variance volume was generated. In table 2.3 a list of the parameters used to generate the cube is shown. The cube shows higher values (depicted as lighter areas in figure 2.20), where geological discontinuities such as faults, channels etc. are present.
Figure 2.20. Variance or coherence slice at 400ms. Straight line segments between inlines 900 -1100 and in the upper right corner (white arrows) reveal the presence of faults.

In figure 2.20 a coherence slice is displayed. The figure shows several faults (indicated with arrows) and few channel-like features. The later are extracted and parameterised further in the next chapters.

Table 2.3 Main parameters used to generate the variance cube

<table>
<thead>
<tr>
<th>Type of seismic input</th>
<th>16-bits reflectivity data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference horizon</td>
<td>Hardebank (fine-tuned)</td>
</tr>
<tr>
<td>Time windows</td>
<td>30 ms</td>
</tr>
<tr>
<td>Gate size in x direction</td>
<td>5 traces</td>
</tr>
<tr>
<td>Gate size in y direction</td>
<td>5 traces</td>
</tr>
</tbody>
</table>

2.5.5. Acoustic impedance cube.

The reflected amplitude volume was transformed into an acoustic impedance volume (Staatsolie document). The Constrained Sparse Spike Inversion algorithm was used to perform the inversion (Debeye, 1990). This algorithm models the input data as the convolution of the wavelet and an acoustic impedance model representing the geology. A unique user-driven impedance fairway constrains the variations of impedances both vertically and laterally. Known geologic and geophysical information such as the tectonics and the lithofacies, their acoustic properties, and their rock densities, etc were used to guide the inversion.
A 3D geologic model constructed specifically for the project was used to extract the low-frequency information. The horizons interpreted by Staatsolie and a framework table describing the structural relation of the horizons defined the model. This model was populated with well log information; logs were extrapolated according to expected geologic structures and stratigraphy.

For this model the wavelet was extracted using well log information (Staatsolie document). The method is used to remove the effects of the wavelet from the input seismic data and generate the acoustic impedance data that is calibrated to well data. This method obtained well-defined rock units and suppressed much of the noise. A sub-volume of covering the entire seismic survey area and was inverted. The results include two seismic volumes of acoustic impedance, one in time domain and the second in depth domain. In addition the estimation of the wavelet obtained (figure 2.21).

Quality control of the inversion from reflectivity to acoustic impedance traces was done by Schram de Jong (2003). This analysis includes the comparison of acoustic properties for individual lithologies derived from a large number of wells (example well 3T08 in figure 2.22). In figure 2.22, traces from the AI volume at well location (A) was compared to the product of the sonic velocity and bulk density on the wireline logs (B).

Examples of cross sections in time domain (slice A) and depth domain (transverse slice B) are shown in figure 2.23. At the intersection of both sections the density log (RHOB) from a well 3T08 is displayed (see well log interpretation in appendix B). Tie-in of seismic images with well logs is crucial in this project. An approximation of 1m (true vertical depth TVD) ≈ 1ms (two ways travel time TWT) can be used with an acceptable margin of error, but thanks to the short well spacing and thickness of the study interval, where the reservoir is located, a more accurate velocity model can be derived. The horizontal scale indications in 3D images (very often in this document) are only approximate.
2.6. Tie in of seismic with well data

Well data play an important role in the 3D analysis of the field regardless of the one-dimensional nature of this information. Wells are the ground truth when used as constraining points. The lithological information extracted from the logs has to be tied in with 3D seismic data in order to identify the seismic reflections. The values of sonic velocities and density obtained during well logging, from which the acoustic impedance of the layer is calculated, together with other layer properties like resistivity or natural radioactivity, set the basis for the development of a simple but effective model to tie in seismic and logs.

The extreme values of the well logs (sonic velocity, bulk density, resistivity and gamma ray) are used to recognise extreme matching values in the seismic responses.

The following are general rules used to tie in the well log with the seismic traces (these rules are applicable only to a limited depth range 300 ~ 450 ms):
The top of a layer of very high density is matched with a strong trough in the reflectivity data, or a high local value of the acoustic impedance.

The top of layer with very low density and high natural radioactivity (high values in the gamma ray logs) is matched with a high peak in the reflectivity seismic trace and low values in the acoustic impedances.

The highest resistivity values are associated with the presence of oil in the study interval. Unfortunately, the presence of oil is not detectable in the seismic images.

When a layer is present twice it is associated with the occurrence of a compressional fault and the lower layer is used as a marking point.

Because the Hardebank shows a distinct response to one of the criteria above, we applied the rules to this sedimentary unit. For each well the depth of the Hardebank was estimated, based on the density of this layer and the overlying strata; and the corresponding trough in the reflectivity data was matched.

An example of a well log interpretation and the corresponding seismic are shown in figure 2.24. The well log and seismic interpretation are those supplied by Staatsolie.

The rules were also applied to identify the top Cretaceous unconformity. The seismic signature of this layer is not as pronounced as for the Hardebank, and the Gaussian shape of the peak is wider, making the identification more complicated.

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4 The data is zero phase, and is displayed according to European (normal) polarity convention meaning that a trough represents the transition from a slow to a fast layer.
In some areas, lignite layers are present between the Hardebank and the top Cretaceous. These lignite layers have low densities and high gamma rays values. Where such layers are present, they can be used as quality control for the tie-in between seismic and well data. Pronounced peaks in the gamma ray curve revealing the presence of a lignite layer (left curve in figure 2.18) have to match low acoustic impedance values or with peaks at the boundary of a lignite layer with other lithofacies.

In figure 2.25, an example of three wells tied in with a 2D seismic image is displayed. The figure shows three wells with their density logs, and an acoustic impedance slice. At the study interval level the match is acceptable. The 3D nature of the seismic dataset used in this research, allowed for a well correlation and tie-in of seismic data with well data also to 3D. This is described in the next chapters.

**Figure 2.24.** Example of the tie-in of well logs with seismic data.

**Figure 2.25.** Example of the acoustic impedance section together with the density logs from wells 3t06, 3t07 and 3t08. The approximate positions of the markers: top Cretaceous (TC) and Hardebank (HB) are indicated (See colour version of this figure in appendix C).
3. **Visual analysis and segmentation of the seismic data**

Geological bodies are inherently three-dimensional. Through advances in subsurface data acquisition technology, high-resolution three-dimensional geological data sets can be acquired. An example of such a high quality data set is the high resolution 3D seismic from the Tambaredjo Oil Field.

3D visualization has developed as a powerful tool within computer science and became indispensable in many application areas including geology (WorldOil, 2005). 3D visualization of environments and processes has two main advantages: improved perception and hence better and faster interpretation of the available information. In this work the iCenter (Schlumberger) at the department of Geotechnology (Delft University of Technology) was used to perform a detailed visual segmentation and analysis of 3D seismic data. The characteristics, specification and software possibilities of the iCenter can be found in appendix A.

Although a partial view of the 3D shape of geological objects can be obtained in outcrops, they fail to reveal the full three-dimensional information. Seismic volume images on the other hand will never exhibit the same amount of detail as outcrops, but their true 3D nature adds an element that cannot possibly be obtained from outcrops. An HRS object is a 3D representation of the envelope of a sedimentary body at a scale that depends on the frequency with which the survey was acquired.

In this chapter, methods, algorithms, and tools that have been used to visualize the HRS data are presented. Some of the 3D system tools that have been incorporated in the workflow to analyze the 3D data are described as well. Here a visual analysis of the data and an immersion into the different volumes available is accomplished.

Part of the HRS recorded in the Tambaredjo field (very high resolution compared to most of the 3D surveys recorded worldwide) visualized with the 3D visualization software can be seen in figure 3.1. It depicts four seismic sections together with a small volume window. By combining slices and volume windows a general overview of the data can be obtained. Nevertheless the full delineation of the object boundaries requires more processing. In order to reach the optimum visualization of the 3D seismic data it is necessary to segment the data volume into meaningful geological bodies by means of image processing.
The segmentation of images plays an important role in the processing workflow of three-dimensional seismic data sets. Objects are isolated in order to be studied in more detail and subsequently parameterized. Hence the importance of developing software tools to segment images and identify object boundaries. Several methods and tools for the segmentation of 3D images can be found in the literature (Russ, 2002). Methods applicable to seismic interpretation include: volume window visualization, region growing, propagation, level sets methods, and active surfaces.

The basic principles of these tools and how they were adapted to the available data set are described next. The methodology applied in the segmentation and later in the interpretation is also presented.

### 3.1. Segmentation of image volumes

The volume window is an image cube that permits visualization of the 3D nature of seismic objects (see figure 3.1). A volume window is a subset of the entire volume. The size and shape of a sub-volume are freely varied depending on the sub-volume characteristics. It can be a cube, a rectangular parallelepiped or a cuboid. In practice, the user can adapt its size in order to cover the desired 3D sub volume in which objects of interest are located.

The volume window is an ideal tool for volume rendering. Volume rendering has become an important tool for real-time 3D seismic interpretation (Engel et al., 2001; Castanie et al., 2005). Volume rendering tools combining different output volumes produce results that can

---

**Figure 3.1.** Visualization consisting of four seismic cross-sections from the AI volume, and a volume window through the study dataset, where a channel like object can be recognised (white arrow, see colour version of this figure in appendix C).
be effective in seismic interpretation (Marsh et al, 2000). Multi-modal data sets can be used not only for volume rendering, but also for voxel based clustering and classification as will be described in the next chapter.

Using the volume windows it is easy to perform interactive colour manipulations for enhancing objects and finding the optimum colour setting. In order to find an optimum colour setting, the histogram has to be displayed (see figure 3.2). Manipulation of the histogram offers the operator the possibility to interactively adapt the colours to the interesting amplitude intervals in the histogram.

![Figure 3.2. Volume window visualization of the acoustic impedance inside a “pizza” box on the left and the histogram panel for changing the colour lookup table on the right(See colour version of this figure in appendix C).](image)

Making the window transparent to amplitudes outside the selected intervals facilitates displaying 3D objects of interest, and allows the operator to isolate individual image segments. A non-transparent image segment is an isolated 3D object that can be analyzed, measured, and parameterized. Such a 3D shape in full extension cannot be obtained from outcrops, which makes 3D visualization a new and valuable tool for geological data analysis and interpretation.

Using the so called “growing windows”, layers and objects with very high amplitude or acoustic impedance (AI) values have been extracted. It is important to consider the specificity of the dataset, or the lack thereof. Seismic data (reflectivity and AI) have a nearly Gaussian distribution (see figure 3.2) and with the help of the data histogram, the operator can manipulate the colormap in order to get the layer isolated from the (transparent) background. Figure 3.3 shows an example of a volume that was segmented in such a way that layers and objects with high acoustic impedance values are isolated. Since all relevant information is contained between the extremes, object extraction by histogram manipulations is a tedious task. Methods that are capable to overcome this problem, such as the growing algorithm, will be applied and are presented next.
3.2. Segmentation of image volumes using the region growing algorithm

The region growing algorithm (Myers & Brinkley, 1995) is a valuable tool to segment image volumes. The method can group voxels within a certain amplitude range that are connected to each other in the image space, while the other voxels remain transparent. After defining a seed point at a certain location (voxel), an amplitude range is selected in both the depth (time) and the horizontal directions. The seed starts growing and neighbouring voxels are added only if their amplitude is within the specified amplitude range. This process can be iterated a fixed number of times or until convergence is reached. It yields an image segment in the 3D data set that satisfies the selection criteria and that should correspond to a geologically relevant element.

In addition to the amplitude criteria, the growing process can be bounded by pre-defined surfaces (one or two if necessary or depending on the availability). In these cases, only the voxels between (above or below) the surfaces are considered. This option allows adding geological knowledge to the algorithm. It assumes that a surface is a layer that was deposited in a specific period of time, which forms a “time” boundary in the growing process and therefore also in object segmentation. The assumption that the surface is a layer that was deposited in a marked and relatively short period of time is used to create a parameter space that helps to identify geological objects. This parameter space is called “GeoTime” cube and will be described in detail in chapter 5.

Figure 3.3. Rough segmentation using a volume window. The example shows an image segment, which shows part of a meander loop of a river (dotted curve), where the inner bank deposit has a noisy boundary and/ or has been eroded/cut by tectonic activities. The approximate positions of the markers: top Cretaceous (TC) and Hardebank (HB) are indicated.
The region growing algorithm has been used to isolate objects such as layers and sedimentary objects. The performance of the growing algorithm depends heavily on a set of growing parameters. A method to select the parameters of the region growing algorithm, which are essential for obtaining a relevant segmentation result, was developed.

The sequence of steps can be summarized as follows:

1. Estimate the number of classes $N$ that are present in the image data using the lithological information available in well logs and cores.

2. Cluster the data values into $N$ classes and calculate for each class C1, C2, … CN the minimum and maximum amplitude value.

3. Calculate to which class (C1-CN) the seed point belongs. This class is named “class S” (CS).

4. Start growing by adding the neighbouring points if the amplitude is between the minimum and maximum value of class S.

5. Vary the amplitude range and analyse the results with the purpose of finding an amplitude interval for which the number of voxels added in the growing process does not change significantly.

6. Vary the number of classes $N$ if the optimum amplitude range for segmenting the object is not found and continue with step 2.

Figure 3.4. Segmentation result of the region growing algorithm showing a channel with crevasse splays.
Chapter 3

An example of objects found by the region growing algorithm can be seen in figure 3.4. Here a channel with crevasse splays is isolated from the background, resulting in an interesting image segment corresponding to a channel complex that will be studied in more detail in the next chapters.

Figure 3.5 shows the total number of voxels in the extracted channel (figure 3.4) as a function of the amplitude range to accept neighbours in the growing algorithm. The flat interval of the curve is interpreted as indicating the optimum amplitude range for extracting the channel.

The growing can be limited to one single voxel in the depth direction, which results in a surface rather than a volumetric object. This allows the creation of a seismic horizon. Horizon picking is a very common task in conventional seismic interpretation, but it is not easy and time consuming.

Figure 3.5. The total number of voxels in the extracted object as a function of the amplitude range for accepting voxels by the region growing algorithm.

### 3.3. Segmentation of the image volume by 3D interpretation of surfaces

Interpretation of the sedimentation at a specific surface or geological time window can bring new insights into understanding the geology of the field area. A 3D view offers a better perception of the environment that is being visualised. The analysis of the interpreted surfaces can reveal interesting patterns that play an important role in the seismic interpretation process. Following an event that covers a relatively large area and is composed of a layer that was deposited in a specific, short period of time brings outstanding information to the interpreter.

A 2D image cannot always follow a layer or reflector which is by nature not planar. Useful information is obtained by following the irregularities while creating a surface and visualizing it in 3D, as depicted in figure 3.6. In this case, all details related to an individual horizon, including the discontinuities caused by tectonics or other geological processes can be observed. Surface visualization in a 3D system turns out to be a very powerful tool to study the morphology of the seismic horizons present in the Tambaredjo field. In this work, the interpreted surfaces helped solving the following tasks:
• Marking depth or two ways travel time (TWT) intervals

• Understanding the sedimentation at a particular level or a geological time window

• Identifying faults

• Generating a new parameter space called GeoTime cube.

Irregularities of surfaces may contain important information to better understand geological processes. In order to facilitate this, interpreted surfaces can be “painted” with seismic values: reflectivity or acoustic impedance. Sedimentation processes are depicted along surfaces and the mapping in 3D shows interesting details like for examples: possible subdivisions of the field area shown by different colours on figure 3.6. The subdivisions can be related with the East – West fault systems or possible palaeo-coast.

Figure 3.6. 3D view of a surface with interpreted fault sticks in the southern part of the field. The surface is seen to dip towards North. This image covers the entire survey area (83 km²).
Figure 3.7. Topographic irregularities along the surfaces. In the top surface a crescent shape object broke the continuity of the layer, possible caused by a river, which formed a point bar.

Sharp cuts in surfaces are often linked to faults, since no other geological process can create such a straight boundary. In an area not affected by tectonic movements, the surface should be homogeneous in terms of its seismic response (monochromatic in the 3D image depicted in figure 3.8). The white arrows in figure 3.8 indicate a line along which the surface is vertically displaced. This is characteristic for a fault.

Figure 3.8. Fault visible in the surface.

In the new parameter space, the GeoTime cube (chapter 5), the volume between two surfaces will be flattened and thereby such fault throws will be eliminated.
3.3.1. Method for surface tracking in 3D

Surfaces can be created manually, but in this work they have been generated automatically using the surface growing tool (see appendix A). This tool has some advantages over manual interpretation such as an immersive 3D view of the surface generated and a reduced time for surface delineation (the growing is done in a few seconds to a few minutes depending on the size of the volume). On the other hand, there are also disadvantages with respect to manual surface interpretation, because the result will in general contain gaps. These missing image segments need to be interpolated to produce a smooth version of the interpreted horizon.

There are several methods for surface interpolation. A kernel-based method called “Normalized Convolution” (Knutsson & Westin, 1993; Westin, 1993; Westin, 1994), which is also used to reconstruct images where pixels are missed, has been successfully applied. This method works as follows: in the first step, the surface creating algorithm is used. In the second step, all points belonging to a surface are connected from a selected point on a reflection that appears to be continuous over a large area. The algorithm generates a surface joining all the voxels labelled in the previous step. The surface generated in this way contains gaps and/or peaks. The gaps are the black holes seen in figure 3.9. At the position of the gaps the properties of the selected reflection appeared to be outside of the pre-defined amplitude range.

The surface is extracted, and a 2D image is made, in which the intensity value is the height of the point compared to the base (the bottom layer of the volume). Mathematically, a single surface is a two-dimensional function \( z(x, y) \). Positions \((x,y)\) when a value is missing correspond to a gap in a surface. In order to fill the gaps, first a binary image called the confidence function \( c(x, y) \) is created as follows:

\[
c(x, y) = 1, \text{ if } z \text{ exist and } 0 \text{ if } z \text{ does not exist.} 
\]

(3.1)

Secondly, a kernel \( h(x, y) \), slightly larger than the gap sizes is created. The kernel is band-limited with a circular symmetric shape and effective radius \( r \). A Gaussian filter, with standard deviation \( r \) was chosen. The Gaussian filter has unique properties in forming a scale-space (Witkin, 1983), which is beneficial to surface interpolation since it does not introduce spurious detail.

The extracted surface is multiplied by the confidence function. The interpolation is now performed by the convolution of this signal with the kernel \( h \), and normalized by the convolution of the confidence function \( c \) with the same kernel \( h \).

\[
s(x, y) = \frac{[z(x, y)c(x, y)] * h(x, y)}{c(x, y) * h(x, y)}
\]

(3.2)

where \( s(x, y) \) is the interpolated surface and * the 2D convolution operator.

An example of surface interpolation is depicted in figure 3.9
3.4. Visual improvement by processing the seismic images

Seismic images represent different geological processes. The original reflectivity volume as well as the acoustic impedance volume show significant lateral discontinuities that can be interpreted as caused by erosional processes and lack of accommodation space for sediment deposition. An effort to increase the quality of the data to improve subsequent geological interpretation is carried out by image processing, exploiting both low-level as well as high-level operations. “Low-level operations” have an image as input, and produce an image as output. “High-level” operations produce models and parameterizations, and are applied to image segments or alternative data structures. The stratigraphic interpretation of a seismic image can be improved by correcting the image for post-sedimentary processes, such as faulting or compaction. Different image manipulation techniques were tested in this work. Manipulation of images ranges from image processing, image analysis to image understanding. Image processing operations can be divided into four categories: operations based on the image histogram, simple mathematics, filter operations such as convolutions, and nonlinear techniques such as mathematical morphology.
A workflow where a seismic image is the input was designed. The workflow returns newly produced images, measurements and image descriptions at the output. A sketch of this workflow is depicted in figure 3.10. The processing steps in the workflow, include all the operations applied to the original seismic data or/and combination of attributes, with the purpose of achieving better image quality.

A large set of image processing tools have been applied to the seismic images to improve the image quality and to facilitate the identification of seismic facies. After a careful analysis of output images, it was decided to apply several steps to process individual images. The succession and order of the developed sequence may vary depending on the type of object that has to be tracked.

Figure 3.10. Sketch of the workflow for data processing and interpretation. The processing steps in the workflow, include all the operations applied to the original seismic data or/and combination of attributes, with the purpose of achieving better image quality.

The objective was the extraction of objects that correspond to the main seismic facies identified in the Tambaredjo seismic data set. These facies are described next; and the image processing tools that form the sequence used to enhance the visualization and/or detect the target lithofacies is presented as well. The individual object extraction and classification at object level is described in chapter 5.
3.5. Visualization of seismic facies identified in the dataset

Interpretation of the seismic facies in the 3D Tambaredjo data set was limited to the facies present in and close to the reservoir, the study interval\(^5\). The two main reflectors limiting the study interval are the top Cretaceous unconformity and the Hardebank. Within this interval, the T-sands are the objects of the greatest interest for reservoir characterization.

3.5.1. The top Cretaceous unconformity

The lowest and therefore oldest surface is the top Cretaceous unconformity formed by erosion of the underlying sequence, with acoustic impedance higher than overlaying Tertiary reservoir sands (see 3D view in figure 2.17). It is a sand, with pore plugging by kaolinite, giving it a higher density and velocity that the T sands. This surface is present over the whole field area. The acoustic impedance of the unconformity does not always increase sharply, the exact nature of the layer (tightness, density, and velocity) changes from place to place, related to the palaeosol conditions.

---

\(^5\) The study interval includes not only the reservoir interval, but also all the lithologies present in the interval delimited by the top Cretaceous unconformity and the Hardebank, those two reflections are considered the boundaries. For simplicity, it is often referred as reservoir interval.

**Figure 3.11.** Detection of the top Cretaceous (TC) by applying a Gaussian filter followed by the Kuwahara filter: A original B after processing. Scales are in arbitrary units starting at the lower left corner.
Since the primary interest is on layers above the unconformity, it was extracted using the growing surface tool. The growing tool was not applied directly to the original image, but the data was first filtered using the Gaussian filter\textsuperscript{6} with $\sigma=3$ to suppress the noise and small scale structures. Next, a Kuwahara filter of size 3 (Kuwahara et al, 1976; Bakker, 2002) was applied to enhance the boundary between the top Cretaceous unconformity and the sands deposited on this unconformity (see figure 3.11).

The final result can be seen in figure 3.12 where the top Cretaceous unconformity is stripped from the sediments deposited on top of it. The erosion marks are now well visible, as is a fault.

\textbf{Figure 3.12.} 3D visualization of the Top Cretaceous unconformity. The layer stripped from the sediments deposited on top of it. A fault is visible from the right to the centre of the image. The approximate position of the Hardebank (HB) is indicated.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3_12.png}
\caption{3D visualization of the Top Cretaceous unconformity. The layer stripped from the sediments deposited on top of it. A fault is visible from the right to the centre of the image. The approximate position of the Hardebank (HB) is indicated.}
\end{figure}

3.5.2. Hardebank

The extensive calcareous layer called Hardebank is the clearest marker found in the dataset. This layer has a density around 2500 kg/m$^3$, which is the highest value for this interval in the well logs. This layer has also the highest sonic velocity in the interval, as well as a remarkable high value of acoustic impedance (compared to surrounding layers in a time gate). Similar to the top Cretaceous, the Hardebank is a layer that extends almost over the entire field area as can be seen in figure 3.13.

The best way to extract the Hardebank is again with the region growing algorithm. The algorithm is applied to a processed image. The processing sequence applied was very similar to the one used to extract the top Cretaceous unconformity. It consists of a Gaussian filter with $\sigma=3$ and a Kuwahara filter of size 3 too. The layer extracted by this sequence is depicted in figure 3.13.

\textsuperscript{6} Filter sizes are expressed in voxels. Multiplying with a voxel-spacing (chapter 2, table 2.2) yields the corresponding physical sizes.
Sharp cuts in figure 3.14 reveal the presence of faults. The southern part is upthrown with respect to the northern part, which also shows generally lower amplitudes than the southern block. The large East-West fault system can be recognized by visualizing the Hardebank surface in 3D. The interpretation of this system is depicted with sticks in figure 3.14.

![3D view of the Hardebank](image)

**Figure 3.13.** 3D view of the Hardebank extracted with the region growing algorithm applied to pre-processed volume and subsequently smoothed. The fault present in the Top Cretaceous unconformity (figure 3.12) is also seen here.

Further interpretation of the Hardebank layer resulted in the identification of a second East-West running discontinuity in the middle part of the 3D image depicted in figure 3.14. This feature could be another minor fault system, or a palaeo-coast line.

### 3.5.3. T-sands

The oil bearing T-sands have acoustic properties that are in the middle of the entire range of the data set. This makes their interpretation and extraction difficult. The velocity and density of the T sands are also comparable to those of clays, with which they are typically associated. A more detailed analysis of acoustic properties of the lithofacies found in several wells was done by Schram de Jong (2003).

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7 Figure 2.15 (chapter 2) shows that the acoustic properties of the layers located in between the top Cretaceous and the Hardebank are very similar.
Figure 3.14. East-West fault system that divides the Tambaredjo field into two parts (See colour version of this figure in appendix C).
Figure 3.15 depicts the sand units in the production area 3O24. The sands are deposited on top of the Cretaceous unconformity (surface in figure 3.15). This is an area with high tectonic activity. Tectonics influenced the deposition of the sands; the large accommodation space was due to syndepositional faulting in this zone. In this area, several wells were drilled meaning that a large amount of information is available. This information has been used to classify the lithofacies present in the study interval as described in the next chapter.

![Figure 3.15](image-url) T-sand units in the production area 3O24 with high tectonic activity and several wells drilled. Tectonics influenced the deposition of the sands; the large accommodation space was due to syndepositional faulting in this zone (See colour version of this figure in appendix C).

For the extraction of the sands, a sequence of image processing filters was developed. This produced satisfactory results comparable to the results that will be presented in chapter 4. The sequence is composed of a uniform filter of size 3 (Gonzalez et al., 1992), and 10 iterations of a Coherence Enhancing Diffusion filter (Weickert, 1999). The result, an example of which is shown in figure 3.16, shows layers that match with sand layers identified on well logs.

![Figure 3.16](image-url) Comparison of the T sand mapping using image processing sequence (large section A) and the Artificial Neural Network of chapter 4 (smaller cross section B). The approximate position of the markers: top Cretaceous (TC) and Hardebank (HB) is indicated.

The thickness of the T sands can vary laterally as can be seen in figure 3.16. Nevertheless, the sands are mostly interconnected, indicating that they have formed through amalgamation of several small channels that flowed in the same general direction. Figure 3.17 shows three such
channels in the northern part of the field, where a smaller percentage of interconnection is observed compared to the sand sheet in figure 3.15 that is located in the Southern part of the field.

![Figure 3.17](image.png)

**Figure 3.17.** A sand unit formed by three channels with their corresponding crevasse splay deposits.

3.5.4. **Lignites**

The low bulk density of lignite layers slows down the propagation of seismic waves compared to the surrounding lithologies. Lignite layers are mainly responsible for the lower part of the acoustic impedance histogram. By visualizing only the lowest acoustic impedance values, it is possible to map the lignites, if their thicknesses are larger than the vertical resolution of the data. Lignites are present in the Palaeocene, but they are not laterally continuous. Often, in well log records, a lignite layer is found separating T1 sand from T2. The thickness of the lignite layers in the target interval falls below the resolution of the seismic data and they are not of interest for reservoir characterization.

3.5.5. **Other lithologies present in the reservoir interval**

In the reservoir interval different shales are found, which are formed generally as muddy floodplain deposits. Shales in the Tambaredjo reservoir are composed of kaolinite, smectite chlorite and illite (Staatsolie internal documents). There are also layers composed of clayey sand and sandy clay in the wells and cores. The shales are difficult to extract and isolate, because they have acoustic properties comparable to sands (or clayey sands and sandy clays). They are not part of the objectives of this study.
Interactive analysis of seismic facies using 3D visualization provides a better perception of the geological objects, and helps to significantly speed up the interpretation of images (considering that visualizing a 3D image is equivalent to simultaneous visualization of a set of 2D images). However, the extraction of the sand bodies, which are the principal features of interest, requires a more sophisticated tool. Therefore, Artificial Neural Networks were chosen as the tool to investigate this further.
4. Voxel-based classification of seismic facies\textsuperscript{8}

The Tambaredjo data set includes high-resolution seismic data and well logs as described in chapters 2 and 3. After visualisation as discussed in chapter 3, the next step was to find a proper way to group the voxels of this data set into classes that correspond to meaningful entities: the facies. Clustering and classification methods were employed to accomplish this task.

For the classification of seismic facies a volume was created in which the basic unit is a grid block or voxel. The sizes of the grid block in $x$ and $y$ directions are the inline and crossline spacing of the seismic survey (see table 2.2). The $z$-axis in seismic surveys is expressed in two ways travel time (TWT) and in the Tambaredjo survey the unit block size along the $z$-axis is 1 ms. The acoustic impedance volume was converted from time to depth and in this volume we have a $z$-axis block size of 1 m.

4.1. Clustering of seismic data

The Tambaredjo data set is very large which poses a computational problem for some methods of clustering. Three well-known unsupervised clustering algorithms and a supervised classification method capable of processing large data sets: $K$–means (Tau, & Gonzalez, 1974), ISODATA (Tau, & Gonzalez, 1974), and Artificial Neural Networks (Hertz et. al., 1991, Haykin, 1994) were applied.

$K$-means clustering is an unsupervised classification method. It clusters the voxels by assigning them to the nearest class mean. The initial number of classes – denoted by the parameter $K$ – as well as the initial position of the class means can be determined by the operator based on the task at hand. We choose to evenly distribute the initial class means in the data space and then iteratively cluster the voxels into the nearest class using a minimum distance technique. In each iteration the position of the class means is recomputed and all voxels are reclassified with respect to the new means. All voxels are classified to the nearest class unless a standard deviation or distance threshold is specified, in which case some voxels may be unclassified if they do not meet the selected criteria. This process continues until

\textsuperscript{8} Parts of this chapter are based on two M.Sc. Theses at Delft University of Technology: Haverkamp (2002) and Schram de Jong (2003).
convergence occurs. Other stopping criteria that were used are: comparing the difference of the number of voxels in each class during the last iteration with a predefined threshold; or after the maximum number of iterations is reached.

An example of unsupervised classification using the $K$-means algorithm is shown in figure 4.1.

![Figure 4.1](image)

**Figure 4.1.** Cross section of the clustered voxels using the $K$-means algorithm for a number classes equal to seven in the study interval (excluding the Hardebank and Top Cretaceous): a) original AI slice. b) Result of $K$-means clustering based on the AI (See colour version of these figures in appendix C).

ISODATA clustering, resembles $K$-means clustering. It is an unsupervised classification method that initializes the class means as evenly distributed in the data space and then iteratively clusters the voxels using minimum distance techniques. Again, each iteration recalculates means and reclassifies voxels with respect to the new means. Where as the number of classes remains fixed during $K$-means clustering, the ISODATA algorithm allows iterative class splitting, merging, and deleting based on a comparison of cluster statistics with predefined threshold parameters. Similarly, all voxels are classified to the nearest class unless a standard deviation or distance threshold is specified, in which case some voxels may be unclassified if they do not meet the selected criteria. Like in $K$-means this process continues until the number of voxels in each class changes by less than the selected threshold or if the maximum number of iterations is reached.

An example of unsupervised classification using the ISODATA algorithm is shown in figure 4.2.

In both examples ($K$-means and ISODATA) the voxels are clustered based on the measured property (seismic amplitude or acoustic impedance) or a set of computed attributes (e.g., seismic instantaneous attributes). In the case of $K$-means the number of classes was set equal to 7, based on this information from the wells. For ISODATA we let it vary from 5 to 10. In the second approach a minimum and maximum number of classes is specified. This is more realistic because the number of lithologies varies from one well to another. In Tambaredjo not more than 10 different lithofacies occurs at the study interval but always at least 5 including the Hardebank and the Top Cretaceous basement.

The best results were found using Artificial Neural Networks as will be described in the paragraphs below. Because of their effectiveness in the clustering of seismic data we used the
ANN not only for clustering the seismic voxels, but also a supervised classification of the seismic dataset into facies using the available well log information was carried out.

Figure 4.2. Result of an unsupervised classification using the ISODATA algorithm for a minimum number of classes equal to 5 and a maximum equal to 10. The cluster that is visualised can be interpreted as sand, the light colours below can be interpreted as top Cretaceous (TC) and the light colours above as the Hardebank (See colour version of this figure in appendix C).

4.2. Artificial Neural Networks

Artificial Neural Networks (ANN) are a different paradigm for computing, because they are inspired by the parallel architecture of the human brain (Wasserman & Oetzel, 1990). Artificial Neural Networks can be considered as an architecture for a multi-processor computer system composed of simple processing elements with a high degree of interconnection. The simple processing elements communicate with each other using scalar messages. The inter-processing connections offer adaptive interaction between the elements.

A single human neuron may have thousands of different inputs, and may send its output represented for example by the presence or absence of a short-duration spike, to many other neurons. Neurons are wired up in a 3D pattern and a human brain is many orders of magnitude more complex than any artificial neural network considered so far.

In the last 20 years ANNs have experienced a major development in their applications to fundamental research (Simpson, 1990). This rapid progress was not only caused by advances in computer technology, but mainly thanks to the ability the networks have for solving pattern recognition problems and making predictions.

Artificial Neural Networks are used in geosciences to solve a wide variety of tasks (Poulton, 2001; Sandham & Leggett 2003). Particularly, they have been applied with success to assist geologists in seismic interpretation and reservoir modelling (Aminzadeh, 2000; Grennberg et al., 2001; Nikravesh et al., 2003). They are used as classifiers for facies recognition. In this chapter, the images are classified at the voxel level using Artificial Neural Networks. First, the ANNs are used for unsupervised clustering of the seismic data. The segmentation by
unsupervised clustering of voxels yields a partitioning of voxels into geologically meaningful objects. These objects will be the subject of study in later chapters. Such clustering is in fact a way of data reduction.

4.3. Unsupervised classification using ANN

From the visual analysis of the Tambaredjo data set it became obvious that seismic responses are not random but that their distribution correlates with geological meaningful patterns. In order to cluster the seismic responses in the study interval, an unsupervised segmentation using an ANN was made.

The ANN clusters the input seismic signal into a predefined number of clusters. As input data was used the complete seismic waveform, represented by a series of amplitudes within a defined time gate. Each of the resulting class centres is therefore also characterised by a series of amplitudes, i.e. a waveform shape. The number of classes is a user-defined parameter.

A trace signal can be described by an analytic signal, which can be expressed mathematically by a time dependent complex variable \( u(t) \)

\[
u(t) = x(t) + iy(t)
\]

(4.1)

where \( x(t) \) is the trace signal itself and \( y(t) \) is its quadrature (Yilmaz, 1987; Brown, 2004).

From equation 4.1 instantaneous attributes are computed for each point in the data set and will form a so-called attribute vector that holds the properties of that point. Haverkamp (2002) has demonstrated that no relation could be established between a single instantaneous attribute and a reservoir property i.e. the thickness of the sands. However single attributes show features that could be related to geological objects.

4.3.1. Unsupervised Vector Quantiser

The neural network used here belongs to the type of Unsupervised Vector Quantisers (UVQ) (Haykin, 1994), an unsupervised learning algorithm. The general aim of such a network is to find structure in the data themselves and thereby extracting the relevant properties or features. Similar input vectors must be classified into the same category. The classes are found by the network itself from the correlation of the input data. Therefore these networks are often referred as self organizing networks.

The UVQ topology is composed of a vector quantiser part and post processing part. The vector quantiser part consists of two layers, the input layer with \( L \) nodes (\( L \) is the number of elements in the input vector) and a hidden layer with \( K \) nodes (\( K \) is equal to the selected number of classes). These layers are connected via so-called excitatory connection weights between elements of the prototype vectors.

The post processing layer compares the net outputs of all hidden nodes (classes). The hidden node with the smallest net output is designated the winner. The weighting vector associated with the winning node is updated using the standard competitive learning rule, which means only the winning prototype is updated. The updating is continued until no noticeable changes in the prototype vectors are observed. In the application phase, the output layer consists of
two nodes: one giving the index number of the winning node, and one giving a degree of match between the input vector and the prototype vector of this node. The network generates the following two outputs: the index of the winning hidden node, which is the output class to which the input vector is assigned, and the certainty of match that indicates how close the input vector is located to the centre of the class.

4.3.2. **UVQ horizon based segmentation**

The UVQ segmentation can be done in two modes: horizon based using the seismic trace waveform or volume based, using a set of attributes per voxel. The horizon based approach was used here; this approach needs a well defined and well picked horizon. Any inconsistency in the horizon interpretation easily becomes stronger than the variation in waveform along the horizon. A UVQ applied along a well defined horizon can very well show subtle changes in waveform, i.e. geology, in the defined interval relative to this horizon. If the horizon is not well defined a 3D approach is recommended.

The neural network was trained on a random number of example locations along the entire horizon. Next the trained UVQ network was applied to the full horizon. At each location the network generated two output values; the index number of the winning segment and a degree-of-match. The latter value indicates how close the input trace resembles the centre of the winning segment, and varies between 0 and 1 (perfect match).

4.3.3. **Results of the unsupervised classification**

The unsupervised classification using the waveform within a constant time window at the reservoir interval was done for different time gates and for a different number of classes. A study area of approximately 13 km² was chosen for this experiment. The area is located between inlines 200 – 875, and crosslines 5–500. Figure 4.3 shows the result of an unsupervised classification using the UVQ applied to the waveform at the time gate [-4,12] ms from the Hardebank, where the number of classes was set to 7. The time gate size was chosen based on the wavelength estimated from the extracted wavelet (see chapter 2). In this figure 4.3, two channel-like features can be recognised (arrows).

Interpretation of UVQ segmentation results suggests that seismic lithofacies in the reservoir interval are not randomly distributed, but that they display patterns produced by sedimentary systems.

They can be classified with reasonable accuracy into a relatively small number of classes. A priori knowledge of the number of classes is an important input parameter for the unsupervised classification. This number can be smaller than the number of lithologies (7 – 10) known from wells, considering the limited vertical resolution of the seismic traces compared to the well logs. The density and sonic velocity of several lithologies present in the field are very close to each other and their separation requires a much higher resolution than present in the seismic survey.

---

9 The Hardebank grid was fine-tuned in order to reach the requirements for the horizon based segmentation using UVQ.
4.4. Supervised classification

The wells drilled in the developed areas of the Tambaredjo field provide a set of control points that can be used for calibration. In order to make use of this information, a supervised classification method is applied to partition the data into classes that correspond to the
lithologies identified from, well logs (Schram de Jong 2003). An ANN that belongs to the type of feed-forward back-propagation Multi-Layer Perceptrons\textsuperscript{10} (MLP) is used for this task.

4.4.1. Structure of the ANN MLP

Most supervised classifications by ANNs use MLPs, i.e. feed-forward neural networks whose parameters (weights and transfer functions) are set in a separate training phase by an algorithm usually of back-propagation type. During training, the MLP learns how to transform the input data of a training set into a desired response. After training, the MLP applies this transform function to new samples in order to assign them to one of the classes. MLPs with one or two hidden layers and a sufficient number of nodes can approximate virtually any input-output mapping. They have been shown to approximate and even surpass the performance of optimal statistical classifiers in difficult non linear problems.

This network is organized in three layers, the input, hidden and output layer (Figure 4.4). The input layer consists of 10 nodes. These are six seismic attribute values, to be specified later, the location of the trace ($x$ and $y$ co-ordinates), the true vertical depth (TVD) and one bias node, which is added to the network to have an extra degree of freedom. A single hidden layer of sigmoidal neurons is sufficient to approximate a continuous function with arbitrary precision (Cybenko, 1989). The hidden layer is fully connected to all the nodes in the output layer, which has five output nodes representing the five lithologies of interest.

![Multilayer Perceptrons structure](image)

**Figure 4.4.** Multilayer Perceptrons structure.

4.4.2. Output layer

The response in the output layer is the lithology classification. The first objective of this classification is to assign all voxels to one of the lithologies present in the study interval. The five lithologies targeted are: the Hardebank, the lignite, the clays, and the two sand units, i.e.

\textsuperscript{10} The MLP and UVQ implementation used here are from OpendTect software (http://www.opendtect.org).
the lower T1 and upper T2 sand. Each voxel, at a position defined by inline, crossline and true vertical depth, receives a value per output node that represents the probability of the corresponding lithology to occur at that point. This results in five probability cubes, one for each lithology, corresponding to a 3D matrix for each lithology that indicates the likelihood of that particular lithology at every position in this matrix.

4.4.3. Training set

The quality of the training set for the ANN, implemented in the form of a so-called “pickset” in OpendTect, is essential for obtaining good results. Therefore, the training set must be as representative and as complete as possible. It is a collection of input vectors (seismic traces or attributes) and their corresponding output vectors (lithologies).

A relatively small area of approximately 1 km$^2$ in the 3O24 cluster was selected to perform the experiment (see figure 4.5). The area has a high number of wells (27) with high quality logs. The area contains a variety of geological features of interest: a large number of faults, and differences in sedimentary environments. A subset of the wells was reserved for quality control to test the ANN performance after training was completed.

![Figure 4.5](image)

Figure 4.5. Selected area (small rectangle) to perform the experiment in the 3O24 drilling cluster, where the locations of few wells are pinpointed with green vertical lines (See colour version of this figure in appendix C).

The training set for the supervised neural network was prepared from the well log data, where lithology and the corresponding seismic signal to certain location are known. A large number of picks for each lithology was allocated in the seismic volume (see table 4.1). In order to tie the wells accurately to the seismic volume, the seismic data set was converted from time to depth.
Table 4.1. The number of picks present in the training set for each lithology in the seismic volume.

<table>
<thead>
<tr>
<th>Class</th>
<th>Lithology</th>
<th>Picks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hardebank</td>
<td>202</td>
</tr>
<tr>
<td>2</td>
<td>T1 sand unit</td>
<td>243</td>
</tr>
<tr>
<td>3</td>
<td>T2 sand unit</td>
<td>176</td>
</tr>
<tr>
<td>4</td>
<td>Lignite</td>
<td>75</td>
</tr>
<tr>
<td>5</td>
<td>Clays(^\text{11})</td>
<td>236</td>
</tr>
</tbody>
</table>

In order to train the network, the input data are passed from the input layer to the hidden layer and then to the output layer. The activation function used by the network is a monotonic non-decreasing sigmoid function, which yields an output value for each node bounded between 0 and 1. For each training instance, the final output value of the network is compared with the desired output value. If there is a difference between the network output and the desired output value, the weights of the individual connections are adjusted. This process is repeated until the classification error is acceptably small for the data in the training set. This error is calculated from testing the network on a test set, a subset of 5% of the training set data generated by software. After the ANN is trained, it can be used to classify the previously unknown input data for prediction.

4.4.4. Input layer

The input for the ANN consists of different attributes of the seismic signal. The acoustic impedance cube instead of the seismic amplitude (reflectivity) volume was used for the supervised segmentation, and the attributes therefore, have a different meaning than in reflection seismic. The acoustic impedance signal carries information on intrinsic lithological properties of a layer instead of the lithological contrast between two layers.

![Acoustic impedance, inline 1115. Image size 320 CDP x 70 m.](image)

Although a neural network can deal with redundancy in the input data, the optimal input set is considered to be the set requiring the minimum number of different attributes to identify a particular lithology. After examining the differentiation potential (by comparing the responses) at well locations of available attributes, the following attributes were selected:

**Signal power**: it measures the energy of a trace segment and is calculated from the sum of the squared sample values in a specified time gate, divided by the number of samples.

\(^{11}\) This class includes various types of clays present in the reservoir interval.
Laplacian of the signal: This is a second derivative filter commonly used for edge enhancement. The sharpness is determined by the filter size. The filter coefficients specify how the input samples contribute to the output value. In a 3x3x3 Laplacian filter, the output is calculated by multiplying the central sample value with 26 and subtracting all surrounding sample values. The effect of this operation is zero if all sample values are equal and non-zero (either positive or negative) when a discontinuity is present at the central position.

Velocity fan: The velocity fan filter calculates signal energy with apparent velocities inside a specified velocity range. It supports three options: pass low velocities (i.e. suppress high velocities), pass high velocities and pass velocities within a specified band. A low pass velocity fan filter (2000 m/s) was chosen. The filter, of size equal to 3, means that the data is convolved with a 3x3x3 kernel. Example of a filtered image is shown in figure 4.9.

Mathematical difference stack: The mathematical difference stack subtracts the Laplacian of the signal from the acoustic impedance.
Amplitude average - The amplitude is averaged over a 3x3 (inline/crossline) fully steered cube. This will acts as a filter for the acoustic impedance cube.

Figure 4.11. Amplitude average calculated for inline 1115. Image size 320 CDP x 70 m.

Laplacian of the similarity: Similarity is a form of "coherence" that expresses how much two or more trace segments resemble each other. A similarity of one means the trace segments are completely identical in waveform and amplitude. A similarity of zero means they are completely dissimilar. If the trace segments are considered to be vectors in hyperspace, similarity is defined as the Euclidean distance between the vectors, normalized by the average vector length. The trace segments are defined by the time gate and are found by steering from the reference point to the specified trace positions. Positions are specified in relative numbers. The extension parameter determines how many trace pairs are used in the computation. Two similarities are computed: for the specified trace pair and for the pair that is obtained by 90 degrees rotation. The average similarity of these pairs is returned and a Laplacian is applied to this result.

Figure 4.12. Laplacian on similarity calculated for inline 1115. Image size 320 CDP x 70 m.

4.4.5. Connection weights

The connection weights between the input layer and the nodes of the hidden layer after training are listed in table 4.2. These values are used by the network to calculate the probability cubes for the different lithologies. Each input node corresponds to a single attribute and is connected to three hidden nodes.

Table 4.2. Connection weights in the neural network

<table>
<thead>
<tr>
<th>Input nodes</th>
<th>Hidden node 1</th>
<th>Hidden node 2</th>
<th>Hidden node 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal power</td>
<td>3.89836</td>
<td>2.52759</td>
<td>2.75494</td>
</tr>
<tr>
<td>Laplacian</td>
<td>-1.95072</td>
<td>3.2237</td>
<td>-4.44881</td>
</tr>
<tr>
<td>Velocity fan</td>
<td>7.76643</td>
<td>-1.92884</td>
<td>4.27704</td>
</tr>
<tr>
<td>Mathematical difference stack</td>
<td>2.82339</td>
<td>-3.37828</td>
<td>4.30251</td>
</tr>
<tr>
<td>Amplitude average</td>
<td>-2.02224</td>
<td>-7.56303</td>
<td>1.4611</td>
</tr>
<tr>
<td>Laplacian of similarity</td>
<td>4.85534</td>
<td>-2.15609</td>
<td>3.87174</td>
</tr>
</tbody>
</table>
All attributes used in this network have connection weights to the hidden layer that are roughly speaking in the same order of magnitude, meaning that they contribute to the network more or less equally. In the initial trial-and-error selection process, all attributes with a negative influence on the classification results, for instance those related to frequency and dip, were left out. Also the attributes with a positive contribution to the results, but with connections weights to the hidden nodes of less than |0.1|, were left out to reduce the network’s computing time.

4.5. Results of the supervised classification: probability cubes

The output of the neural network is a 3D probability cube for each lithology. In order to visualize the lithologies, a certain range of the probabilities has to be selected by setting a threshold. A particular threshold confines this range. A threshold of 50% was chosen because above this threshold the lithologies at the well locations in the studied volume match the lithologies from the well logs.

4.5.1. Quality control

To evaluate the ANN’s performance in classifying lithologies, well data are used as control points. We distinguish between control points that were included in the training set and those that were not part of the training set. Since the first subset was used for training the neural network, it can be expected that the network will find the right lithologies at these locations. For the second subset, the control points that were not part of the training set, we can test if the network after training is capable of generalization, i.e. prediction of correct lithologies in new data. The classification was checked well by well for each lithology in order to find discrepancies between the manual classification of the control set and the network classification results.

4.5.2. T1 sand

The ANN correctly classified the voxels at the T1 level in the wells, where the T1 unit was found. The results of such quality control shows that T1 sand is located at the correct position in wells 6P01, 6P03, 6P04, 6P07, 6P09.1, 6P10, 3T01, 3T02, 3T05, 3T06, 3T08, 6K21, 6K23, 3O22, 3O24.1 and 3O25. Discrepancies are found at several other locations and these are described below and illustrated in figures 4.13 – 4.22. The column called ‘network’ is the classification by the ANNs; the column called ‘manual’ is the manual log interpretation that was used as training input for the neural network.

The manual interpretation indicates the presence of T1 at 1209 - 1246 ft in the well 6P08. The network does not find the T1 sand at 1221 - 1226 ft. On figure 4.13, the gamma ray increases, the density decreases and the resistivity decreases over that interval, all responses typical for shale. The network interpretation is probably more accurate here than the manual interpretation.

In well 3T10 the network detects the T1 sand at 1190 - 1200 ft (figure 4.14), while -according to the wireline logs- there should be clay (with very high kaolinite) content. In the training set, this is actually a clay interval. Considering the log response (see fig. 4.15) the network overruled this training data probably erroneously. The T1 sand at 1208 - 1218 ft was detected correctly.
The T1 sand detected in well 3T07 (figure 4.16) is slightly thinner than what the logs indicate. The 15 ft (1190 - 1205 ft) thick sand pack is only 5 ft (1195 - 1200 ft) thick, according to the network’s classification, probably because of the lower resistivities found at this level. The network therefore, might be probably over-trained in areas exhibiting high resistivities.

**Figure 4.13.** Well 6P08, depth interval 1209 - 1246 ft.

**Figure 4.14.** Well 6P06, depth interval 1213 - 1236 ft.
Figure 4.15. Well 3T10, depth interval 1190 - 1208 ft.

Well 6P05 shows a similar T1 response (figure 4.17). Here again the network only detects the T1 sand where it has a high resistivity. The T1 interval, according to the logs is at 1196 - 1220 ft (24 ft). The neural network finds the T1 sand only at 1210 - 1220 ft (10 ft).

In well 6P02 there is only one sand body identifiable on the logs (figure 4.18). This sand is considered T1 sand, because it is situated immediately on top of the Cretaceous unconformity, at about the same depth as the surrounding T1 sands. The network detects the sand interval, but classifies it as T2 sand. The interval can be part of any T1 or T2 sand.

Figure 4.16. Well 3T07, depth interval 1190 - 1205 ft.
Classification...

In well 3T04, the network assigns to a sand interval a high probability for being T1 sand, but also for being T2 sand. Because there is no relationship between the probability cubes for T1 and T2, the network can assign high probabilities of T1 and T2 to the same sand interval. This is the case here: the T2 sand is classified T1 as well as T2. This also happens in well 6K22. Such dual classification has to be solved in post-processing.

### 4.5.3. T2 sand

The analysis of the T2 classification by the ANN at control points turned out to be as follows: The T2 sand is located at the correct position in wells 6P03, 6P04, 6P06, 6P08, 6P09.1, 6P10, 3T01, 3T02, 3T04, 3T06, 3T07, 3T08, 3T10, 3O22, 3O24.1, 3O25, 6K21 and 6K22. Discrepancies are found at the wells described below.

![Figure 4.17. Well 6P05, depth interval 1196 - 1220 ft.](image1)

![Figure 4.18. Well 6P02, depth interval 1196 - 1217 ft.](image2)
In well 6P07, two T2 sand bodies (1190 - 1197 ft and 1202 - 1206 ft) were interpreted on the logs (fig. 4.19). The network only detected the upper sand body, while the lower sand body remained undetected. The 4 ft thick sand interval is probably too thin to be present on the acoustic impedance volume. The resolution or detection threshold was estimated to be larger than 2 m for lignite, and from this example the same detection threshold may apply for the sands.

In well 3T05, the T2 sand is interpreted at 1160 - 1171 ft from the wireline logs (figure 4.20). The neural network only detected the lower part (1166 - 1171 ft) of this interval. This lower part has a lower gamma ray and a higher resistivity than the upper part. Apparently, this upper part (1160 - 1166 ft) is too clay-rich for the network to be considered a sand.

**Figure 4.19.** Well 6P07, depth interval 1190 - 1206 ft.

**Figure 4.20.** Well 3T05, depth interval 1160 - 1171 ft.
Like in well 3T10, the network detected some sand at an interval where according to the wireline logs clay is present (figure 4.21). The network was trained to detect clay over that interval, but the network apparently overruled the training set. The network was not trained on different clay types.

The problem that occurred in well 6P02 is discussed in the previous paragraph. A sand interval was interpreted on the logs as T1 sand, while the network classified it as T2. The network overrules therefore the training set.

In addition to what has previously been said about 6P05 (the network only detects the part of the T1 sand interval (see fig. 4.14) where it has a high resistivity (1210 - 1220 ft), the network calls the sand interval with the lower resistivity (1196 - 1210 ft) T2 sand. Conversely, there may have been manual misclassifications.

Figure 4.21. Well 6P01, interval 1196 - 1211 ft.

Figure 4.22. Well 6K23, depth interval 1180 - 1199 ft.
A thick kaolinite-rich clay layer in well 6K23 (fig. 4.22) is classified as T2 sand by the network. This is a problem encountered in more wells. Since the network has not been trained on detecting kaolinite and clay separately, it cannot distinguish between sand and clay when kaolinite is present.

4.5.4. Hardebank

For the ‘Hardebank’ excellent classification results were obtained. The Hardebank classification is in accordance with the training set in every well. This is not particularly surprising, since the layer has very high acoustic impedance that stands out against all other lithologies. The Hardebank is used to tie in seismic with well logs as described in chapter 2.

4.5.5. Other lithologies

The ANN was not able to detect the lignite layer because the (average) thickness of the lignite in the reservoir is below the resolution or detection threshold of the ANN.

The trained ANN was found to have difficulties with the detection of clays. Few points in the clay’s probability volume exceed the threshold of 50%. This may be caused by the fact that the output class “clay” in reality contains many different clay types. Instead of putting more effort in optimizing the network’s clay detecting performance, it was assumed that everything in the sequence that is not classified as Hardebank, sand T1 or sand T2, is by default clay. This can certainly be justified from a production point of view.

4.5.6. Summary of the ANN classification results

When comparing the ANN output with manual classification of the well logs, it appears that the ANN can detect the sands (T1 and T2) of thickness greater than 2.5 m quite reliably. The network can accurately detect the Hardebank because of its unique properties. The network, however cannot detect lignites because of insufficient vertical resolution. The ANN was not trained to detect the different types of clay.

The network sporadically detects sand intervals that have a high probability to be either T1 or T2 sand. These sands have similar attributes and another tool must be used to distinguish them. In places where the sand has a low resistivity the network fails to detect the sand. Discrepancies between the log interpretations and the ANN can be attributed to noise in the data.

4.6. Visualization of the classification results using the 3D visualization facility.

Using the 3D visualization system, mentioned in the previous chapter and described in more details in appendix A, the output volumes generated by the ANN supervised classification can be visualized. The two sand volumes are shown in figures 4.23 – 4.24.

Figure 4.23 shows a 3D image of the T1 sand as detected by the ANN. The T1 sand lies above the top Cretaceous unconformity. The shape of the unit is sheet-like, but with differences in thickness. The thickness of the T1 sand varies laterally quite strongly because it was deposited on top of the irregular unconformity, having greater thicknesses in depressions of the surface. Nevertheless, the sand is for a large percentage connected, as can be seen in figure 4.23. The T1 sand is probably deposited by multiple channels whose flow directions
initially depended strongly on the topography, but at a later stage mostly followed the regional drainage towards the north.

Figure 4.23. Extracted volume of the T1 sand in the 3O24 area (see figure 4.5). White means high probability.

Figure 4.24 shows the extracted T2 sand in the study area. This sand shows a rather different picture from the T1 sand. It is much less sheet-like and shows objects that are interpreted as point bars (arrows). The T2 sand is interpreted to be deposited by meandering rivers in a setting perhaps similar to today’s coastal plain of Suriname.

Figure 4.24. Extracted volume of the T2 sand in the 3O24 area (see figure 4.5). White means high probability.

In the next chapter, a classification at object level is described, where object boundaries are delimited and patterns based on geometry are studied. In chapter 6, a methodology to parameterize the identified channels and point bars is presented.
5. Geological object recognition in fluvial systems

Geological objects exhibit characteristics that are related to the object as a connected set of elements, i.e. the voxels that compose the object in an image of the subsurface. These characteristics cannot be extracted from individual voxels, but need an initial segmentation of the data set. The supervised voxel classification of chapter 4 classifies each voxel into a lithology. Connected sets of voxels that were classified as the same lithology are a first attempt to object identification. The accuracy of boundary delineation can be increased and object attributes that allow them to be classified into a geologically relevant body can be computed. Classification at the object level is the recognition of an object with size, shape and properties that are geologically meaningful and resemble known geological features. The extraction of such objects from a subsurface data set is not a simple task. Very little information about the sedimentation and erosional processes that took place in the underlying field area is available, although these processes may exert an influence on the final shape and dimensions of the geological objects. In addition to these processes there may be many other sources of noise involved that hamper segmentation and subsequent recognition of the geological objects. Here, the attention was focused on the analysis of the 3D geometry of relevant seismic features that resemble objects of interest for reservoir characterization. A sequence of image processing operations to delimit object boundaries has been developed. The segmented objects can be classified into geological bodies by measuring meaningful signatures. Patterns in modern analogues from the literature were used to build geological models that helped in this difficult task.

The object extraction process will be followed by the parameterization of the extracted objects as will be described in the next chapter. Nevertheless, the design of the object extraction and the object parameterization processes should not be scheduled as isolated tasks. Rather than placing these tasks in a series interconnection (called “open-loop”) they should be placed in a feedback interconnection (called "closed-loop") in which they can learn from each other. Appropriate modern analogues were used to design parameterization models of the geological objects because they are not affected by erosion and tectonics and because they are suitable to extract geometrical parameters and other relevant information.

The first step in the geological object recognition process was limiting the solution space to the reservoir interval. With this step, the attention was concentrated on a relatively small time/depth interval. The delimitation of the study interval is done by two markers: the top Cretaceous unconformity and the Hardebank (both have been described before). Image analysis of those two surfaces has shown that features at those boundaries are important to be
considered in the interpretation process. Restricting the geological object search to the geological time windows between the Hardebank and top Cretaceous surfaces (see figure 5.1) yields a substantially reduced data volume. Reducing the geological time window to a certain period of time, the Palaeocene in this case, means that only geological processes that occurred during this period are considered relevant to understand the depositional environment, which is fluvial in this case, with some transitional marine influence. The typical depositional bodies, characteristic for fluvial environments (Schumm, 1977; Reading, 1986; Miall, 1996) and the spatial patterns that those features form were the priority of this research.

![Reservoir interval delimited by the two seismic markers Hardebank and top Cretaceous unconformity (See colour version of this figure in appendix C).](image)

**Figure 5.1.** Reservoir interval delimited by the two seismic markers Hardebank and top Cretaceous unconformity (See colour version of this figure in appendix C).

### 5.1. Pattern recognition in the seismic images

Analysis of seismic images is a key task in the seismic interpretation process as described before in chapter 3. Detailed analysis consists of identifying patterns that can assist in the prediction or the identification of the lithology. Connected sets of voxels with similar local properties form characteristic spatial patterns in the images. These spatial patterns can be translated into geological patterns caused by the sedimentary processes, which determined their shape and dimensions.

In fluvial environments, the typical bodies that can be found include: sand sheets, channel fill deposits, point bars and other fluvial bars, crevasse splays, levees, abandoned channels and oxbow lakes. Frequently such bodies are found in areas where accommodation space was available. An object-driven approach has been used, inspired by the 3D nature of the geological objects to be found and by the characteristics of the 3D data set. Surfaces were employed as boundaries, in order to delimit the search space in the depth/time direction. Tectonic movement and erosion have been considered as processes that affect the channel belt systems in the Tambaredjo field.
Surfaces and faults are the most common geological features that can be recognized and interpreted in seismic images. Their associated patterns can display continuity or discontinuity of sedimentation layers as described in the previous chapter (see also figures 3.8, and 3.13). The continuity and discontinuity of spatial patterns are recognizable in all available volumes, including the output volumes obtained by applying the supervised ANN. The results from the ANN also show a feature that is typical for compressional thrust faults. These can be recognized by a duplication of a layer in a vertical well (see example in well 6p10, appendix B). Figure 5.2 shows the layer with the fault throw. The observed repeating of the Hardebank in wells drilled in this area can be explained from this figure.

Figure 5.2. The Hardebank extracted by the supervised ANN reveals the presence of faults in the reservoir interval. In the lower corner a displacement of the layer by a thrust fault can be observed causing it to occur twice in the well 6p10 (see appendix B) drilled in this 3O24 area.

Other geological features have other seismic patterns associated with them, which allow their recognition. This study is limited to specific objects, reducing significantly the search for spatial patterns, and providing guidelines that help in the detection, segmentation, and characterization of such reservoir bodies. Other geological features, not directly related to hydrocarbon reservoirs, have been studied to a lesser degree.

5.1.1. Recognition of patterns formed by geological objects in channel belt systems

Channel fill deposits, sand sheets, point bars and crevasse splays found in channel belt systems form often good hydrocarbon reservoirs. In the seismic images several objects with shapes and signatures associated with ancient channel belt systems can be observed. Newly developed methods are illustrated by examples that were recognized in the data set. The limitation to one specific depositional environment and the geological knowledge associated with it put a limit on wider applications.

Channel fill deposits are common objects formed along the river path. Channel recognition consists of searching for curved patterns displaying a degree of sinuosity in seismic volumes. These curved patterns should be confined to the depth/time vicinity of a particular horizon. The image operations described and used in chapter 3 are essentially filters that reduce noise while preserving characteristic signals such as surface patterns. Nonlinear filters may tune themselves to apparent structures without crossing boundaries. They may even sharpen edges such that the identification and extraction of geological bodies becomes easier.
Coherency Enhancing Diffusion filter, when applied to a uniform filtered version of the acoustic impedance cube, was found to provide good results. Channels filled with sand or mud can thus be recognised from the volumes.

![Figure 5.3](image_url) A channel system, where some crevasse splays can be recognised (white arrows). The channel fill is seen to become wider towards North. Scale indications are approximate.

5.2. Object isolation and boundary identification

In chapter 4, the voxels were clustered and classified into lithofacies based on well log information. The results of this classification are probability output volumes per lithology that provide a solution space for the geological objects of interest. This segmentation is more accurate than the one obtained from using growing algorithms and volume windows.

By combining all available information, the layer boundaries are defined with higher accuracy; objects that have a geological meaning are extracted and can be translated into geological terms based on their geometry and acoustic properties. This is a crucial task in the object driven-approach.

Several techniques can be used to separate individual objects from their surroundings, often referred to as background, and to refine boundaries between object and background. Defining transparency and/or opacity transfer functions to the probability volumes produced by the ANN, points to the necessity of having a clear definition of object boundaries. The opacity level selected draws a boundary, but this boundary can be changed by adjusting the threshold.
5.2.1. Method for object boundary identification

First attempts for object boundary delineation in this data set were done using standard methods. The simplest method used to identify the boundaries of a seismic object is by setting a threshold on the mapped parameter, e.g., the reflected amplitude or acoustic impedance. A single threshold or a double threshold has been used, which permits selecting a range of the image values. The amplitude selection method defines the boundary by first plotting the number of voxels in the selected volume as a function of the threshold value and then finding a region in the curve which is more or less flat. The flat part denotes large gradients at the borders which are a good indication of the presence of a boundary. This method for object segmentation is fully automatic and yields by definition a connected set of voxels.

In order to refine the identified boundary edge detection filters were used. Edge detection filters such as the one proposed by Canny (1986) allow an accurate localisation of edges in the presence of noise. They work well in the presence of blurred edges caused by partial volume effects, i.e., the “physical size” of a voxel overlaps the true boundary between object and background. Edge-preserving smoothing filters such as the Kuwahara filter (Kuwahara et al., 1976) suppress noise and simplify the image, which may in turn help to identify image edges. Applying edge filters to seismic objects improves the edge localization inside the rough boundary interval produced by thresholding. Edge detection filters reduce an interval of a certain size to a unique boundary position at every cross section. In the case of seismic data, the available geological information can be used to restrict the solution space. The input data set will be modified as described below.

Combining all these techniques, a method to find the interval where true boundary lies was developed. This approach uses the following steps:

1) Make a rough, initial segmentation of the object

2) Apply a dilation filter (Soillé, 1999) to the initial segmentation mask

3) Apply an erosion filter (Soillé, 1999) to the initial segmentation mask

4) Create a mask for the boundary interval by subtracting the results after erosion from the result after dilation

5) Apply an edge detection filter to the selected boundary interval

6) Identify possible boundaries using an appropriate optimization function

7) Extract the seismic object using the boundaries identified in step 6.

The optimization function of step 6 depends on the particular characteristics of the data. Basically, a set of candidate points is selected in steps 1-5. Each of those m points (or voxels) has n attributes, calculated from the seismic signal or assigned by the ANN as described in chapter 4. An example of a set of candidate voxels is illustrated with the following matrix.
where the set of \( m \) candidate voxels is represented by the \( m \) rows of matrix \( M \), and each voxel has \( n \) attributes (represented as the elements \( x \) in the columns of the matrix \( M \)) that describe the individual voxels.

The task of the optimization function consists of evaluating all the vectors that form the rows of matrix \( M \) and assigning them a value \( p \), which describes the probability of this vector to become a boundary voxel. The voxel with maximum probability \( p_{\text{max}} \) is used as boundary point in step 7. The optimization function is built with the help of methods that assign probability values to individual voxels. The method is different for each object to be classified. The example below illustrates how the entire sequence works.

**Figure 5.4.** Rough segmentation of the channel fill and the crevasse splay (upper left).

The rough segmentation of the objects can be done using the volume windows with colour manipulation and/or the growing algorithm. An alternative is to apply the automated thresholding procedure to one of the probability cubes produced by the ANNs. These tools can be applied to original images as well as to processed images. In the following example (figure 5.4), the rough segmentation was made by applying the growing algorithm to an AI image containing part of the channel fill from figure 5.3 together with a crevasse splay.
Dilated and eroded versions of the segmentation mask are subtracted from each other as indicated in the segmentation recipe. An interval where the boundary is located is thus obtained, and this interval needs to be analysed in order to find the boundary more accurately. For this the Kuwahara edge preserving filter is used.

Voxels in the boundary interval are analysed one by one, and the optimization function, applied to select the voxels with the highest probability to become the boundary voxels, combines the following information:

- original value in the image
- value after applying the edge detection filter
- values of the surrounding voxels.

Finally, a mask with the refined boundary is created and the object was extracted from the original image. The object geometry is analysed and corrections are made if necessary. The fine segmentation is shown in figure 5.5.

**Figure 5.5.** Fine segmentation of the channel with the crevasse splay depicted in figure 5.4.
5.3. Searching in geological time

The solution space can be reduced using the available geological knowledge. It can be implemented by reshaping the data space into geological more meaningful volume. A new parameter space to facilitate the interpretation and particularly the object extraction is developed for this purpose.

5.3.1. GeoTime cube

Because of the irregular shape of the geological markers and the numerous small-scale faults, geological object extraction proved exceedingly difficult. It was therefore decided to create a new volume wherein two well defined horizons with detectable contrast of acoustic properties with the surrounding lithologies (the “Hardebank” marker and the top Cretaceous marker in the dataset) represent the top and the bottom of the volume. These two markers are flattened and the data in between is interpolated so that the volume contains an equal number of data points at each geographic location (see sketch in figure 5.6). If assuming that, to a rough approximation, the two bounding markers of this volume are geologic time markers, i.e. they were deposited or formed over a time period that is relatively short in comparison to the interval in between them, then, the vertical distance in between these markers represents geologic time, albeit not in a linear fashion since the sedimentation rates certainly will have changed throughout the interval. This method of creating a seismic volume in which the vertical axis is geologic time is a full 3-D version of the “stratal slicing” proposed by Zeng et al. (1995, 1998a, 1998b) and of the “proportional slicing” discussed by Posamentier et al. (1996). Stark (2004, 2005) also refers to a volume in which the vertical axis is “relative geologic time” and which he recommends as a method for detailed sedimentological interpretations of seismic data.

Figure 5.6. Schematic sketch illustrating the construction of the GeoTime cube: a) the original seismic data with two geological markers indicated by solid lines and an intercalated geological layer shown by the dashed line; b) the two markers are simultaneously flattened at their highest and lowest point respectively, and the data in between is interpolated. The geological layer is now continuous.

Example of the cube can be seen in figure 5.7. In this area, a very clear dipping of both layers is visible. The upper horizon looks more irregular than the lower one. There is also a relatively large fault in the centre of the image, which affects both horizons differently. None of these effects remains in the GeoTime slice, making it a suitable space for the identification and extraction of geological bodies.
5.3.2. Interpolation function

The interpolation of the data between the two GeoTime cube markers can be done with different methods such as nearest-neighbour interpolation, linear interpolation, or spline interpolation. Because the interval to be interpolated is small (ranging from 15 to ~30 meters), a cubic spline interpolation was chosen (de Boor, 1978; Lee, 1989; Farin, 1997). This interpolation turned out to be very effective. The thickness of the interpolated interval in the resulting GeoTime cube can be freely chosen, and possible choices include: the minimum time difference, the maximum time difference or any other value in between. In order to avoid aliasing in the re-sampling process, the maximum thickness is preferred. This procedure is related to, but different from the horizon flattening commonly used in seismic interpretation. The GeoTime cube is a form of flattening done on two reflectors simultaneously (Figure 5.6). The purpose of this procedure is to facilitate the tracking of objects without the usual disturbances caused by tectonic deformations, and to extract them subsequently. The procedure is reversible, i.e. once extracted, the vertical dimension of the objects can be restored into two-way travel time or depth. For proper volumetric calculations, this step is a necessity. A similar volume can be generated using an “Age Volume”, as detailed in the work of Spark (2005).

Figure 5.7. Comparison of original AI slice (in line in the right), with a slice of the corresponding flattened slice from the GeoTime cube (cross line in the left). Notice that the values outside of the study interval are set to zero in the GeoTime cube. Horizontal scale indication is approximate (See colour version of this figure in appendix C).

5.4. Geological interpretation of the results

A significant effort was made to link the spatial patterns found in the images to geological objects that help to understand the sedimentary processes that took place in the field. Acoustic properties of the subsurface are translated into a reflection image. However, this is not a straightforward noise-free process. The reverse process, i.e. the extraction of acoustic and
other physical properties of the subsurface from seismic images is an even a more complex process.

The object boundary definition described earlier in this chapter can be influenced by the linking process between the object and the geological body that this object represents. Rather than open-loop interconnection between object delineation and object classification, also called a feed-forward approach, a classification-based refinement of the object boundary to fully exploit all possible knowledge from geology into the object segmentation and extraction was implemented. This means that the geology related to an individual object may limit the solution space of the boundary delineation.

The simplest model of the subsurface is a layer-cake model, where the subsurface layers are stacked on top of each other and form a stripe pattern. In such a case, the seismic images would show a stripe pattern too and the link between data and model would only require a set of corresponding points between which one can interpolate. The reality is very different because the seismic data show discontinuities and patterns significantly different from the layer-cake model. These discontinuities and the processes that cause them are of interest.

In this work, an object-driven approach was chosen. In the first place, an inventory of particular spatial patterns and their description of the basic geometrical bodies present in fluvial systems was made. Knowledge of characteristic properties allows the identification of other such objects in the seismic data set. In table 5.1, a list of basic objects and their spatial patterns is given. These patterns should allow their identification in seismic images and their spatial arrangement should lead to a better understanding of the sedimentary processes.

**Table 5.1.** Set of typical geological features in channel belt systems that were recognised in the seismic images.

<table>
<thead>
<tr>
<th>Object</th>
<th>Pattern on seismic image</th>
<th>Geological origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>A more or less continuous reflection caused by acoustic impedance contrasts with adjacent layers. Defines the depositional plane.</td>
<td>A relatively widespread change in the depositional mechanism. Can have taken place over a short period of time. Originally sub-horizontal (the depositional plane).</td>
</tr>
<tr>
<td>Fault</td>
<td>Sharp sub vertical displacement of one or several surfaces.</td>
<td>A differential movement, typically caused by tectonics that broke the geological continuity of the surfaces.</td>
</tr>
<tr>
<td>Channel fill</td>
<td>A sinuous or meandering elongated shape usually in the depositional plane.</td>
<td>Sedimentation in a river channel, typically when is becomes less active. Therefore often fine-grained.</td>
</tr>
<tr>
<td>Point bar</td>
<td>A crescent-shaped feature aligned in the depositional plane, sometimes with eroded ends.</td>
<td>Formed on the inner banks of meandering river bends where flow velocities are lowest.</td>
</tr>
<tr>
<td>Sand sheets</td>
<td>Similar to surfaces, but with less lateral continuity and irregular outlines.</td>
<td>Widespread overbank deposition of sands during flooding, sometimes from several events.</td>
</tr>
<tr>
<td>Crevasse splay</td>
<td>Overall lobe-shaped but irregular in detail, aligned in the depositional plane with an origin at specific points of the river.</td>
<td>Overbank deposition by a local break of the river bank (levee).</td>
</tr>
</tbody>
</table>
Surfaces and faults are not hydrocarbon reservoirs but rather geological boundaries. It is important to mention that they have more than one function in the interpretation workflow used here. Examples of surfaces can be found in figures 3.6, 3.7, 3.13, and 3.14. Horizons identified in the image are represented as a surface and are considered to be geological layers. The importance of surfaces and their functionality was described in chapter 3. The discontinuities found along these surfaces are related to tectonic movements, erosion or another process that causes a discontinuity of the layer. Faults were also described above and their discontinuity pattern is approximately a straight, roughly vertically oriented plane. Figures 3.6; 3.8; and 5.2 show examples of faults.

The shape of the channel fill deposits in fluvial systems match the shape of a river, although they are formed when the river wanes and its bed is filled with fine-grained sediments. Examples are shown in figures 5.3 and 5.8.

![Figure 5.8](channel_fill_deposit.png)

**Figure 5.8.** Channel fill deposit. The deposition was probably affected by a fault that is marked by the dotted line, changing the discharge regime in the lower part of the image.

The dimensions of the sand sheets are difficult to estimate because the boundaries are mixed with other lithologies that have a similar seismic response. A good example of a sand sheet was found by the ANN at T1 level and depicted in figure 4.23 of chapter 4. The T1 sand was deposited on the top Cretaceous unconformity. The sands from different rivers seem to have amalgamated here on top of each other, creating a sheet-like unit.

Point bars are recognised on seismic as objects with a crescent shape when seen from above. They also occur in many modern meandering rivers (figure 5.9). Their shape is not always regular because of erosion, but their main geometry often can be recognized. Because of the
importance of point bars and their potential as hydrocarbon reservoirs, they are studied in more detail in the next chapter. Point bars identified by the ANN at T2 level are depicted in figure 4.24. At this time the rivers (probably) had not sufficient accommodation space to form sand sheets along the whole area, and they deposited sediments in point bars, crevasse splays and channel fills. By contrast, in figure 4.24, accommodation space was created on the downthrown (Northern) side of a fault, leading to a significant thickening of the T2 sands on this side of the fault.

Crevasse splays can be good hydrocarbon reservoirs. They are formed during flooding caused by a break of a riverbank and they can deposit sand over a wide area. The area geometry of a crevasse splay is irregular and therefore, difficult to parameterize. Nevertheless, these irregular patterns make them recognizable on seismic images when they are adjacent to a channel.

![Figure 5.9](image_url) Points bars with visible accretion surfaces (courtesy of USGS).

Individual geological objects say little about the entire sedimentary system. Rather, it is the geometric assemblage, or the mutual relationship, that is of importance. In a fluvial system like the one discussed here, the river channels provide the crucial element, because most other features are linked to them. However, the Palaeocene of Suriname is only a few tens of meters thick, which means that there was a low net deposition rate. Erosion very often removed parts of the sedimentary record, leaving a highly incomplete record.

Where possible, quantification of the geological objects with analytical formulas and comparison with typical dimensions of geological bodies creates a direct link between objects and geology and validates the approach. Other parameters like the alignment of the point bars can provide important information about the main drainage trend. This alignment is derived from the geometry of the detected objects and can be quantified from the seismic images.
6. Parameterisation of geological bodies

Parameterisation of geological objects is one of the main objectives of this project. The Tambaredjo data set offers a unique opportunity to develop models for parameterization of geological bodies because the seismic is of very high resolution and the logs from an exceptionally large number of wells provide validation points. Once objects are isolated, the goal is to parameterise them using a minimum number of parameters. The set of parameters extracted can be used to predict the presence of similar objects in this environment, and to characterize objects with incomplete information.

6.1. Methods for parameterisation of geological objects in channel belt systems

The geological objects extracted from the Tambaredjo data set were very often partially eroded or otherwise affected by post-depositional processes. These incomplete structures cannot be used to define models for the parameterisation. Another problem is that these partially eroded objects have a wide variety of appearances and do not form shapes that can be quantified in a simple way, i.e. by a small set of parameters. It is, however, important to develop a methodology that is capable of overcoming these difficulties. Since recent fluvial systems are much less affected by erosion and tectonics, they can be used as analogues for ancient systems. These recent systems are studied and analyzed with the aid of aerial photography and satellite imagery.

6.1.1. Recent analogues

Figure 6.1 shows a satellite image of the Cosewijne River, located a few kilometres south of the Tambaredjo Oil Field. It is one of many rivers that flow from the Guyana shield northwards into the Atlantic Ocean. These rivers currently do not carry large sediment loads, mostly because the hinterland consists of basement rocks that erode very slowly (the Precambrian Roraima sandstone formation has been largely eroded in Suriname), but also because accommodation space is low under the present high sea level conditions. These rivers meander through mud-rich flood plains in their lower reaches, but they show accretion.
surfaces that indicate point bar developments, perhaps at a time of greater accommodation space, such as the Pleistocene. The present situation is, therefore, to some degree comparable to the one during the Palaeocene, although the large amounts of clay transported from the Amazon river westward along the coast by the Guyana current clearly present a significant contrast to the situation during the Palaeocene, when the Amazon presumably had a very different drainage pattern.

Figure 6.1. Satellite image of the Cosewijne River in Suriname. Although the present level of sedimentation by this river is low, there are clear indications of point bar developments in some of the meander loops.

Other analogues are found in areas where the accommodation space is greater such that sand bodies could develop better. An example is found in the Western Siberian Lowlands. In this vast region there are numerous meandering rivers that range from small to very large. Figure 6.2 shows a single, abandoned meander loop next to the currently active river in the vicinity of the town of Omsk. The snow highlights the accretion surfaces of the abandoned loop, indicating that the entire inner bend belongs to the point bar. This example can therefore be used to evaluate the best parameterisation method for point bars, the principal sedimentary deposits of meandering rivers (Miall, 1996). In another example, shown in figure 6.3, the path of the meandering river can be followed over ten meander loops, each of which shows point bar accretion although not as clearly as in the previous figure. This example can be used to parameterise the channel as well as the point bars.
Parameterization...

Figure 6.2. A single abandoned meander loop next to the active channel of a river in the Western Siberian Lowland. Point bar accretion is highlighted by the difference in snow cover on flat and vegetated land. The photograph has been taken from an airplane and is approximately corrected for parallax. The settlement in the lower left corner gives approximate scale.

6.2. Parameterisation of channels

For modelling the path of a river, natural cubic splines have been used (Lee, 1989; Farin, 1997; Kharab & Guenther, 2002). The natural cubic spline is an interpolation method that connects two adjacent control points. In contrast to other curve fitting methods, each curve segment has a unique equation, while still constraining the curve to comply with the data properties at the control points. At these control points, the spline is continuous and twice differentiable, a property that is needed for computing the curvature along the path of the spline. The average width of a river is easy to measure in the images and, for the sake of simplicity, is here assumed to be constant over the area analysed. A number of properties can be obtained from the spline fit, but the focus of attention was on the variations of the curvature along the channel path. Additional properties to be derived from the imagery include the main drainage trend of the meander belt and the sinuosity (defined as the distance along the channel axis over a certain interval divided by the Euclidean distance from the beginning to the end point of the interval).
Figure 6.4 shows the result of two natural cubic spline fits to the river channel of figure 6.3. The result in the top figure uses a large number of control points, while the result in the bottom graph uses a much smaller number. In the bottom graph, only those points with maximum curvature and the inflection points between the left and right turning loops, are used. The bottom curve still offers a very good description of the river path and is represented by the spline coefficients and the coordinates of the control points only. As is observed, all relevant features are present in the bottom curve despite its sparse representation.

The parameterisation of ancient rivers starts with the extraction of channel voxels in a seismic volume. They are identified using the GeoTime cube and methods described in the previous chapters. Next, the identified channel voxels are modelled as curvilinear objects in which the central path is described by natural cubic splines. The channel width is determined by analysing the voxel properties perpendicular to the channel axis (in the horizontal geotime plane). Here, the average is taken as the local channel width. A possibility is to carry out this calculation at every control point used for the spline fitting, or alternatively to calculate it for the entire interval. In figure 6.5, a channel is shown as an ensemble of voxels extracted from the seismic data set (top), and the channel representation using a minimum number of parameters for the cubic spline fit assuming a constant channel width (bottom). Figure 6.5 also shows that, despite this simple approximation, the comparison between the originally extracted channel and the parameterised model is reasonably good. Important considerations are that the modelled channel is continuous, i.e. the missing segments have been filled in, and the model representation is several orders of magnitude smaller than the seismic data. In cases where the path of the channel cannot be modelled by a single spline curve, it is recommended to subdivide the path into smaller segments that can be modelled using a single spline. This subdivision can be complex, and lies beyond the scope of this research.
Figure 6.4. Curve generated by the natural cubic spline interpolation to model the river channel of figure 6.3 using a large number of control points (top) and a minimum set of points (bottom).
6.3. Curvature along the river path

The considerable natural variation in sinuosity\textsuperscript{13} of rivers is one of the bases for classifying fluvial systems (e.g. Reading, 1986). The curvature of a curve is mathematically defined as the rate of change per unit length of the direction of the curve (Weisstein, 2002). The simplest form of curvature is an extrinsic curvature. In two dimensions, let a plane curve be given by Cartesian parametric equations $c: \mathbb{R} \rightarrow \mathbb{R}^2$, $c(t) = (x(t), y(t))$. Then the curvature $\kappa$ is defined by

$$\kappa(t) = \frac{d \phi}{ds} = \frac{\frac{d\phi}{dt}}{\sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2}} = \frac{\frac{d\phi}{dt}}{\sqrt{(x')^2 + (y')^2}},$$

(6.1)

\textsuperscript{13} Most rivers paths cannot be well approximated by sinusoids, but we maintain the term here.
where $R$ is the set of real numbers; $x, y$ are the Cartesian coordinates of the curve $c$; $t$ is the parameter for curve interpolation (Lee, 1989); $\phi$ is the tangential angle and $s$ is the arc length. As can readily be seen from the definition, curvature is expressed in units of inverse length. Note that the sign of the curvature allows discrimination between changes in clockwise and counter-clockwise direction. For parametric curves as produced by the splines, the term $d\phi/dt$ is eliminated and the curvature is expressed as a function of first and second derivatives of $x$ and $y$ with respect to $t$

$$\kappa(t) = \frac{x'y'' - y'x''}{\left((x')^2 + (y')^2\right)^{3/2}}$$  \hspace{1cm} (6.2)

Special attention to the computation of the curvature $\kappa(t)$ was paid, not only because curvature is an indicator of the amount of bending of the curve at every position $t$ along the river path, but also because one of the goals of this work was to study the sediment deposition in the inner bank of the bended river. If the curvature at every point of a river path segment is approximately zero, then the path is clearly a straight line segment, as no significant “bending” is occurring whatsoever. If the curvature at each point of a specific segment along the river path is approximately constant, a circular arc occurs in the meander pattern, as the bending is uniform at each point of this segment.

The computation of the derivatives that constitute the curvature can be taken at various scales (Witkin, 1983; Koenderink, 1984). The derivative at scale $\sigma$ is defined as

$$x_\sigma' = \frac{dx_\sigma}{dt} = \frac{x(t) * g(t, \sigma)}{dt} \hspace{1cm} (6.3)$$

where $\sigma$ has the dimension length, $*$ denotes the convolution operator and $g(t, \sigma)$ a normalized Gaussian function

$$g(t, \sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{t^2}{2\sigma^2}\right)$$ \hspace{1cm} (6.4)

Using the derivatives at a particular scale allows the proper selection of the curve interval for the calculation, i.e. focus on the meandering loops rather than insignificant local variations caused by noise. This scale parameter will therefore be adapted to the inherent dominant size of the river bends. This works as a feature selection process and yields a robust result that is also independent of the initial set of control points.

The radii of curvatures along the river path are plotted in figure 6.6 and 6.7 for two analogue rivers, and for the ancient channel extracted from the seismic volume in figure 6.8. The radius of curvature is defined by

$$R = \frac{1}{\kappa} \hspace{1cm} (6.5)$$

which preserves the sign of the computed curvature. At a given point on a curve, $R$ is known as the radius of the osculating circle.
Figure 6.6. Radius of curvature along the Cosewijkne River (figure 6.1) computed with scale parameter $\sigma = 5$ as a function of the distance along river path (in arbitrary units). Numbering of meandering loops on the map (top) is the same as on the cross-plot (bottom).
From figures 6.6 – 6.8 it can be seen that for the scale parameter $\sigma = 5, 7,$ and $10$ the curvature is equal or close to zero in the straight-line segments and inflection points between left and right turns. This means that the limit of the radius of curvature goes to infinity in those regions. Otherwise the radius of curvature has a finite value and is approximately constant. This indicates that the meander loops can be modelled by circular arcs whereas their connections can be approximated by straight line segments. A simple manual fit of circles to the meander loops is depicted in figure 6.9. The length of the circular arcs fitted to each loop of the meandering river determines the sinuosity. Here the sinuosity $S$ is found to be larger than $\pi / 2$.

This is very high, since such high values indicate that the channel segments at both ends of a loop get very close to each other. At a certain moment, channel cut-off occurs and the migrating river will abandon the loop and find a new path, after which the process repeats itself. Note that the sinuosity $S$ is dimensionless and by definition greater or equal to one. It is the ratio of two distances: the distance along the river path divided by Euclidean distance between the two ends of the loop.
6.4. Parameterisation of point bars

Point bar deposits are formed by sedimentary accretion on the inner bank of a meander loop. They have a corrugated accretionary topography, the scroll bar, which results from episodic lateral accretion (Schumm, 1977; Reading, 1986; see also figure 6.2). The accretion surfaces represent past positions of the river channel that evolved through time until the meander loop was abandoned. From the previous analysis arises the conclusion that meander loops can be modelled by circular arcs. If a point bar is defined as the sedimentary deposit between an initial and a final position of the meander loop, then its outline can be modelled with two intersecting circles (crescent), shown in figure 6.10. The grey crescent shown represents a two-dimensional model of a point bar. It is defined by four parameters: the two centres of the circles (indicated by c1 and c2); and their two radii. In practice, however, these parameters cannot be directly determined. In order to find these parameters, the outline of the deposited body has to be extracted after which the circles have to be fitted to this outline. Three points...
are needed to uniquely define a circle, hence six points are needed to define two circles. If, however, two of these points are chosen at the intersection points of the two circles (the ends of the crescent), they are common to both circles. Now the outline of the point bar can be determined from only four points (Rivera et al, 2005). These points are indicated as P1-P4 in figure 6.10.

**Figure 6.9.** Circles fitted to the meander loops of the river in figure 6.3. The fits are good approximations to most meander loops of the river path for about half the circle's perimeter, indicating a very high sinuosity. Most connections between meander loops are short and can be approximated by straight lines.

**Figure 6.10.** Two-dimensional model of a point bar.
The approach can be tested with the point bar from figure 6.2. For each distinct accretion line, a circle is fitted by choosing several points along it. The result is shown in figure 6.11. Not all accretion surfaces are accurately described by the fitted circles, because the depositional process varies slightly over time. However, the overall match is considered satisfactory for the intended purpose. A few interesting observations can be made from figure 6.11. First of all, the circle centres, indicated by numbers on the image, have traversed along an almost straight line. Secondly, the circle radii grow slightly as the meander loop evolves over time. There is, however, also an area in the south-western (lower left) area where the fit is less good because the accretion surfaces appear to be more elliptical than circular. However, this area covers less than 10% of the total area of the point bar.

![Figure 6.11. Circles fitted to accretion lines on the point bar, with their centres indicated by dots and numbers. In total 15 circles have been fitted.](image)

The sequence of circle centres in figure 6.11 can be considered the axis of accretion, i.e. the path along which the centre of the meander loop shifts. As a consequence of this migration together with the observation that the radius of the meander loops increases with time (figure 6.12), the sinuosity of the river increases with time. The circular arcs that cover the loops for each successive accretion episode increase, which means that the river will erode successively more of the older sediments. This is clearly visible in figure 6.11, where considerably less than a semi-circle is preserved of the first accretion surface to which a circle was fitted, while slightly more than a semi circle was currently deposited, as shown by the last (rightmost) circle. These active depositional areas are visible as white sandbanks on figure 6.3. A fit of successive circles to the meander loops of that river is shown in figure 6.13. Again, most meander loops grow in size over time, and most circle centres follow a more or less rectilinear path.
The average local flow trend of the channel belt in a meander loop can be defined as being orthogonal to the axis of accretion. This line is parallel to the connection of the end point of the point bar crescent (points P1 and P2 in figure 6.10). Connecting these lines from a number of successive meandering loops, or point bars, gives the average flow trend of the river. Another way of determining the general flow trend is by connecting the circle centres of the most recent accretion surfaces, shown in figure 6.14 by thin white lines. The average of these individual directions over the entire area gives the regional flow or drainage trend and is indicated by the thick white line.
The procedure can also be applied to ancient point bars. From the seismic data set, several point bars were extracted using the methodology described earlier. The lower sandstone interval, the T1 reservoir, has a high degree of amalgamation and suffers from significant erosion which makes it poorly suited for this purpose. The higher T2 layer shows more isolated bodies: channels and associated point bars. A few point bars extracted from the ANN output sand volume (see chapter 4) are shown in figures 6.15 and 6.16. After extraction of these geological bodies, circles are fitted to the inner and outer limits of the crescent. It is obvious that not all are in fact full crescents, but that some parts of them are missing. This happens often towards either end point and is likely caused by erosion. It is, therefore, not possible to determine the end points of the crescent as shown in figure 6.16. The boundary points along the two arcs must contribute to the best fit of the two circles and hence produce the parameters of the point bar.

Figure 6.14. Connecting the centres of the most recent accretion surfaces of the meander loops (thin white lines) and averaging them gives the average flow trend of the river system (thick white line).

6.4.1. Optimization criteria for the crescent model of a point bar.

In principle, the user can choose from several optimisation criteria in fitting the two circle model depicted in figure 6.10 to the point bar depicted in figure 6.15. The fitting can be made more realistic by employing point bar characteristics described in the literature (Schumm, 1977; Reading, 1986; Miall, 1996). The position of the four points can be shifted within a tolerance interval defined by the user (small circles in figure 6.15). Changes in the position of the points change parameters of both circles. The purpose is to minimize the error in the geometrical properties derived from the point bar model. Two optimization criteria were used:

- Equal area criterion: the object and the model have the same area after projection on the closest horizon.
- Boundary point criterion: the object and the model share as many boundary points as possible.
In the first criterion, the model-generated area is calculated using a known equation for the area of an asymmetric lens created by the intersection of two circles (Weisstein, 2002). The position of the four points can be adjusted using either a Monte Carlo method or by optimizing the criterion function using a more efficient algorithm such as the conjugate gradient method. In both methods, the program iterates until the difference in projected area between model and data is sufficiently small.

Although the goal is to describe seismic objects with a minimum number of parameters, one can use more than three points to draw the circles that fit the crescent shape. Since point bars in seismic images are often affected by erosion, the second criterion mentioned above is considered more realistic. The set of points used to draw each circle is chosen such that the model shares more boundary points with the image segment. In this case, the area of the model can be larger than the real area of the (partially eroded) point bar.

![Figure 6.15](image_url)

**Figure 6.15.** A point bar extracted from the seismic dataset, superposed by the crescent model with the initial choice of fitting points, circles indicate the tolerance interval defined by the user.

The results after fitting are indicated by circles in figure 6.16. Here the connections of the centres are shown by straight lines. The normal to their average direction indicates the general trend in the regional drainage pattern by analogy with figure 6.14 and the related discussion. The dotted lines in figure 6.16 represent the alignment of these point bars, defined as the direction from end point to end point of the fitted crescent. It is generally found to point towards the North (North - West in the middle one). The alternate solution, i.e. towards the South, is dismissed for obvious geological reasons. In addition to this, the extracted point bars also are used to obtain their average size as well as their volumes. These parameters are important inputs for stochastic modelling of reservoirs and are summarized in table 6.1.
Figure 6.16. Three ancient point bars from the seismic data in the Tambaredjo field, with grey levels indicating the thickness. The crescent-shaped outline is modelled by two intersecting circles. The straight lines connecting the centres of these circles are used to determine the average drainage trend, which is towards the North.

Table 6.1. Main parameters extracted from the four point bars in figure 6.16

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Point bar 1</th>
<th>Point bar 2</th>
<th>Point bar 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume [m$^3$]</td>
<td>23.9 $10^3$</td>
<td>39.1 $10^3$</td>
<td>69.2 $10^3$</td>
</tr>
<tr>
<td>Surface area [m$^2$]</td>
<td>8.1 $10^3$</td>
<td>13.2 $10^3$</td>
<td>23.4 $10^3$</td>
</tr>
<tr>
<td>Radius of the inner circle [m]</td>
<td>78</td>
<td>66</td>
<td>78</td>
</tr>
<tr>
<td>Radius of the outer circle [m]</td>
<td>82</td>
<td>83</td>
<td>91</td>
</tr>
<tr>
<td>Alignment [$^\circ$]</td>
<td>312-132</td>
<td>29-209</td>
<td>2-182</td>
</tr>
</tbody>
</table>

6.5. Assignment of petrophysical properties

Some petrophysical properties are directly related to acoustic properties. Thus, the density and sonic velocity determine the acoustic impedance. Other petrophysical properties such as natural radioactivity of the rocks, resistivity, and porosity cannot be estimated directly from seismic recordings. The object-driven approach used here suggests that objects from a restricted area with similar seismic responses will have similar petrophysical properties since they are genetically related. Such an approach allows extrapolation of petrophysical properties measured in sparsely sampled wells over larger distances.

Figure 6.17 shows an example of how to assign petrophysical properties to new occurrences of objects based on the information obtained from linked or related objects. Here, the locations of three wells (3T06, 3T07 and 3T08) are highlighted. The log interpretation for these wells can be found in Appendix B. A thick sandstone was found in wells 3T06 and 3T07 and a slightly thinner one in well 3T08. Taking the sand voxels inside a well as seed points for the growing algorithms yields shapes that are typical for sandstone sedimentation in fluvial environments. The central and thicker sandstone looks like a sand sheet formed by amalgamated sand bodies. On the right side, a suggested point bar can be identified; on the left side, a thin channel fill deposit can be recognised. The figure not only shows a very good correlation between the sands in the three wells, but also displays a good match between the sands and the Hardebank positions. Based on the spatial relationship of the objects it is concluded that they have similar petrophysical properties. In this case, the objects in figure 6.17 form a potentially good hydrocarbon reservoir.
Figure 6.17. Sand sheet with three wells (white lines), where the logs confirm the presence of a thick sandstone. Notice a part of channel fill deposit in the left side (dotted curve) and a point bar-like feature (arrow) on the right side of the 3D image segment. The distance between the wells is approximately 200m (See colour version of this figure in appendix C).

6.6. Prediction tools

The purpose of object parameterisation in channel belt systems is to obtain a set of parameters that can be used to predict occurrences outside the control area. Once the set of parameters that quantifies a particular channel and its related point bars is known, the questions that arise are:

- How can the path of the channel beyond the boundaries of the seismic survey be predicted?

- What is the approximate extent of the meander belt system in all directions?

If answers can be found to these questions, then tools are available to predict possible well locations outside of the control area.

6.6.1. Prediction of next loop of the channel

A prediction tool to answer the above questions is proposed here. First, a tool is presented for estimating the channel path in places where this path is not clearly defined in the seismic images due to erosion or acquisition noise, or when it lies outside the seismic survey. This tool combines the natural cubic spline used to model the channel path, the calculated radii of curvature along the river segment, and the main drainage trend. Table 6.2 shows how these parameters are used for reservoir modelling.

Figure 6.18 illustrates the use of the parameters described in table 6.2 to estimate the next loop in the river path. The dashed line in this figure represents the drainage trend and was found by a line fit through all central points of river loops. The drainage trend can be
calculated locally or globally. A local drainage trend means that in the line fitting procedure only a few nearby loop centres were included. Assuming that this trend will not change significantly in the next river path interval, a local estimate gives a better estimate for the next loop. In areas where influences of tectonic movements, topographic changes or other geological processes that influence the river path are expected, the usage the global drainage trend is recommended. In the last case, all points in the line fitting are included.

Table 6.2 Parameter obtained from the models and their use for reservoir model prediction.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spline generated curve</td>
<td>The parametric curve can extrapolate the river path using additional points.</td>
</tr>
<tr>
<td>Radii of curvature</td>
<td>The size of the outer circle in the next meander loop can be stochastically obtained using a value from the distribution of the radii of curvature in the control area.</td>
</tr>
<tr>
<td>Alignment</td>
<td>The alignment is the direction from end point to end point of the fitted crescent and gives a direction where to look for additional point bars.</td>
</tr>
<tr>
<td>Accretion axis</td>
<td>The accretion axis is an indicator of the direction of lateral migration of the river. It is used to estimate the drainage trend.</td>
</tr>
<tr>
<td>Drainage trend</td>
<td>The centre of the outer circle in the next loop should cross the line that approximates the main drainage trend. Either the local drainage trend or the “global” drainage trend can be used.</td>
</tr>
</tbody>
</table>

Figure 6.18. Prediction of the next loop of the spline curve that models the river path. Two solutions: one for the maximum and one for the minimum radius of curvature are shown.
The sequence to extrapolate the channel path consists of the following steps:

1) Draw a circle that matches the arc of the last curve segment $C_l$.

2) Define the next inflection point $P_i$ at the intersection of the circle with the main drainage trend.

3) Draw a tangent line to the circle $C_l$ at point $P_i$.

4) Estimate the radius of the next loop $R$, from the distribution of radii of curvature of the channel spline curve.

5) Draw a circle $C$ with a centre on the line that is perpendicular to the tangent line $T$ and radius $R$ that intersect the last inflection point.

6) Extrapolate the curve from the last point passing and turning at inflection point $P_i$ until the second intersection of the circle $C$ with the main drainage trend line.

Two possible (extreme value) solutions are depicted in figure 6.18. The first solution uses the minimum calculated radius of curvature ($R_{\text{min}}$) and the second solution uses the maximum value of the radius of curvature ($R_{\text{max}}$) calculated along the river path. Other possibilities are the mean or median value of the radius of curvature ($R_{\text{mean}}$ or $R_{\text{median}}$). A stochastic optimization function could be defined, and using this function, all possible solutions can be evaluated.

6.6.2. Prediction of new point bars

Information obtained from point bars can be used to predict occurrences of new point bar-like objects, estimate parameters of the inner bank deposits and also as input for process-based stochastic models. The alignment of the point bars is a direct indicator of the search direction for new point bars. The method described above suggests that a point bar was formed in the inner bank of the estimated loop. Figure 6.19 shows two aligned point bars which show a local drainage of 29 – 209 and 2-182 degrees respectively. These values give the direction along which new point bars can be found. Similar to the river path, the size of the outer circle of a new point bar can be estimated from the calculated values of the radii of curvature of the river's central path.

In the example depicted in figure 6.19, no more point bars towards the North were found, because the river path was affected by the large East-West fault system. The fault changed the conditions for sediment deposition by making more accommodation space, leading to an amalgamated sand sheet at the foot of the fault.

The parameters that describe point bars can be used to study the erosion/deposition rate in the area, which is a parameter often used as input for process-based models. Using the optimization criteria defined earlier in this chapter, two different models for a particular point bar can be generated (each model based on one criterion). An example is shown in figure 6.20, where a point bar is modelled twice using the crescent model. The first model (left) maximizes the criterion of sharing the maximum amount of pixels with the segmented image object while having the same area. The second model (right) maximizes the criterion of sharing the maximum amount of object boundary points between the model and a detected
point bar. The difference in alignment is only 24 degrees. Parameters of both models are listed in table 6.3.

Figure 6.19. Two point bars in the T2 sands of the Tambaredjo data set. A fault caused more accommodation space in the North (arrow) and a different sedimentary pattern. Additional point bars to the South can be projected using the method described in the text.

Table 6.3 Parameters obtained from point bar models depicted in figure 6.20. The volumes are obtained by multiplying the areas by the average thickness determined from the well logs.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Point bar model 1</th>
<th>Point bar model 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area [m²]</td>
<td>6250</td>
<td>7673</td>
</tr>
<tr>
<td>Volume [m³]</td>
<td>18438</td>
<td>22900</td>
</tr>
<tr>
<td>Alignment (degrees)</td>
<td>81-261</td>
<td>105-285</td>
</tr>
</tbody>
</table>

Subtracting the area of point bar model 1 from point bar 2 in table 6.3, an estimate of the amount of erosion $E$ that took place in this inner bank deposit is obtained with the following equation.

$$ E = \text{Volume}_2 - \text{Volume}_1 = 4462 \text{ m}^3 $$  

(6.6)

This estimated amount of erosion $E$ can be used in process base models, where the sedimentary mass balance consideration play important role. Particular characteristics of the reservoir interval in the Tambaredjo field, suggest that eroded and transported sediments are deposited in areas where more accommodation space is found. This is particularly well seen in the example of figure 6.19.
Figure 6.20. Point bar modelled using equal area criterion (model 1) and considering erosion (model 2). The difference in volumes gives an estimate of the erosion that could have taken place in this particular location.
7. Conclusions and discussion

The present thesis has been devoted studying geological objects in a 3D high-resolution seismic data set. An object-driven approach to fulfil the objectives was used.

7.1. Completion of the objectives

The possibility to identify geological objects of interest for reservoir characterization was investigated. For this, a large 3D seismic data set of very high resolution in a shallow, mostly fluvial reservoir was available, together with a large number of densely space wells. Objects with geological meaningful shapes were extracted from the seismic using processing tools that include a 3D visualization facility, image analysis methods and seismic classifiers. These tools helped to visualize and improve the image quality.

Objects were extracted from the seismic data set using different segmentation methods, whereby the most effective ones turned out to be a guided voxel-growing algorithm, and artificial neural network classifiers. The output volumes provide full three-dimensional information. Specific objects such as point bars, channel fills, crevasse splays were identified and extracted. The intrinsic properties of the extracted objects were determined and their geometry was described with a minimum number of parameters. This was done with the goal to obtain results that can be used for predicting reservoir geometries at a larger scale and beyond the study area.

For channel fills and point bars, methods to describe their geometry with a small number of parameters were developed. The method was developed by considering recent channel belt systems of meandering rivers, and was then applied to the data set studied here. The channel fill geometry is described using a natural cubic spline. A small set of points along the channel path is used to generate a curve that models the central path of the river. Points with maximum curvature and inflection points served as spline nodes. Inspection of the curvature along the river path at the dominant scale showed that pieces of relatively constant curvature are connected by inflection points. From this it was concluded that meandering river systems can be modelled by a series of circular arcs that are sometimes connected by a straight segment.

Based on these results, point bars are described using circular arcs that approximate the shapes of the accretion surfaces formed at the inner bank. In order to draw the circle that
contains the arc, only three non-contiguous points are used. The intersection of the first and the last circular arcs form a crescent that models the overall point bar geometry. Optimization of the crescent model was done using two different fitting criteria.

Table 7.1 lists the parameters obtained from the models developed for channels and point bars respectively. These two types of deposits were commonly found in the data set and are shown to be useful for defining the overall channel belt system.

<table>
<thead>
<tr>
<th>Channels</th>
<th>Point bars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central path curve</td>
<td>Inner radius</td>
</tr>
<tr>
<td>Curvature</td>
<td>Outer radius</td>
</tr>
<tr>
<td>Radii of curvature</td>
<td>Area</td>
</tr>
<tr>
<td>Size of the belt system</td>
<td>Axis of accretion</td>
</tr>
<tr>
<td>Main drainage trend</td>
<td>Alignment</td>
</tr>
</tbody>
</table>

Table 7.1 Parameters obtained from the geometry of channels and point bars.

The geometry of the crevasse splays and sand sheets is difficult to parameterize and was not included in this research, although they could often be identified in the data set.

The ensemble of the obtained parameters describes the overall geometry of meandering channel belt systems. The properties obtained allow for a quantitative description of the fluvial architecture and can form the basis for a quantitative comparison of ancient and modern river systems.

7.2. Discussion

In the present work, only one specific environment, i.e. meandering fluvial systems, has been investigated, limiting a wider application of the results. The depositional system of the dataset is characterized by low accommodation space, or conversely by a relatively high degree of erosion. Full preservation of an entire sedimentary body, therefore, is rare. Furthermore, normal faulting as well as slight tectonic undulations of the surfaces complicate the picture, making geological object detection difficult. A method had to be developed that aided in the detection process. Two time markers above and below the interval of interest were chosen to extract the volume sandwiched in between. Flattening the two markers and interpolating the intervals in between resulted in a volume that approximates geological time in its vertical direction, thereby reversing some of the processes that make object detection so difficult. This new parameters space is called GeoTime Cube and it was found that it considerably facilitated the identification and extraction of geological objects.

The methodology to extract and parameterise objects is more or less limited to the sedimentary environment of the data set, but it is scale-independent and has no restriction to data input. The methodology has predictive capabilities, but the extent of the prediction has not been investigated in further detail.

The intrinsic properties of extracted objects can be determined from a simultaneous interpretation of acoustic impedance from seismic and well log data, but this has not been pursued here. Only the connectivity and spatial links between objects was used to extrapolate the intrinsic properties obtained at control points to full object extension.
Further steps could include applications to reservoir modelling and extension to other environments where the individual building blocks of the sedimentary succession can also be identified from high-resolution seismic. Alternative methods of object extraction could be explored as well.
References

Publications


References


MIAILL, A.M. 1996. The geology of fluvial deposits, sedimentary facies, basin analysis, and petroleum geology. Springer Verlag.


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References


Other references


Appendix A: 3D Visualization Tools

At the Department of Geotechnology, there is a 3D visualization centre of the type iCenter from Schlumberger. Its software is called Inside Reality and features the following functionalities:

The main features include the visualization of all data types simultaneously in a common virtual world. The interactive design of well paths directly in 3D space includes real-time drilling and feasibility calculations. The visualization of seismic data is done by slicing in arbitrary directions: a 2D slice in the 3D cube can be visualized in x, y and z direction. That means the image will follow one of the three axes, but the possibility of moving free is also available making the movement of the section free in space and allowing the steering of the slice according to the seismic feature of interest.

The software uses a volume window, which is a sub-volume of the dataset of size arbitrarily defined by the user for real-time volume rendering and multi-attribute visualization. The volume can be made transparent using the colormap tool. This volume window is an appropriate tool for rough segmentation of the image.

The software also allows the dynamic view of reservoir simulation models. If necessary the software has the ability to annotate objects and display images in 3D space. The usage of OpenSpirit (http://www.openspirit.com) platform as independent framework for rapid data access is possible, but it has not been implemented yet.

Visualization of objects

The software was designed using object oriented methodology. It is implemented in a set of objects or classes; and their instances that can be loaded into the framework or abstract class called “World”. The classes of objects that can be visualized in the framework are:

Colormap: it was used to manipulate, edit and scale the colour spectra; and to change the transparency function in a new created or existing colormaps. This tool was used to display the data histogram of the seismic volumes (original seismic data and obtained attributes).

Fence: with the fence tool were displayed vertical sections through a volume, along the horizontal projection of a well path. Data from one of the volumes were mapped onto each section.

Fault: the fault tool was used to interpret faults from the data volume in an interactive manner. A fault is represented as a set of fault sticks and can be visualized by displaying the fault sticks or by a surface constructed by linear triangulation between the control points in the fault sticks (see example in figure 3.6).

Ruler: the ruler tool allowed interactive measurements of distances and orientation.

Slice: the slice tool played an important role displaying planes inside the volume where data is mapped on to.
Surface: They play important roles in the interpretation workflow used in this research work. They were not always generated using Inside Reality, but all surfaces were loaded and visualized with this software. The surface tool performed the visualization of existing surfaces and allowed for manual definition of new simple surfaces, used to constrain the growing tool.

Sketch: the sketch tool was used to create and visualize annotation data.

Volume estimator: with the volume-estimation tool the user can isolate a region in a volume and make real-time volumetric calculations. This tool played important role in the parameter calculations.

Volume window: the volume window tool performs roaming through a volume with a 3D window of adjustable size and resolution. This tool was used to roughly segment the major seismic features.

Wells: the well tool was used to display existing well and well logs and to design new drillable well paths. When designing new well path, the user adds or edits target points where both the position and a corresponding tangent vector can be adjusted. This facility was also used to follow seismic objects like channel like features and to create a fence along such a way generated path.

Reservoir model: Inside Reality offers us the possibility to visualize reservoir models. The reservoir tool is used to display static and/or dynamic models, where dynamic simulation parameters can be viewed as animations. Reservoir modelling was not included in the objectives of this thesis, the tool was not used for this research.

Grower: The growing tool turned out to be a very effective tool for image segmentation and object extraction. It has two implementations: the “Surface Grower” and the “Volume Grower”. With the surface grower we have extracted surfaces, which as mentioned above, played important roles in this research. With the “Volume Grower” we have detected objects of interest for reservoir characterization such as channel fills, point bars, crevasse splays and sand sheets. Both growers help in the detection of faults as well.

The “Surface Grower” detects and isolates seismic horizons from a volume. The tracking process is interactive and fully controlled by the user. After having placed a seed-point, the tool works in either automatic or semi-automatic mode.

The “Volume Grower” detects and isolates connected bodies in a volume. The tracking process is interactive and fully controlled by the user. After having placed a seed-point, the tool works in either automatic or semi-automatic mode. When the growing of one or more bodies has been completed, surfaces can be generated through the top, the base, the maximum value or the minimum value of the bodies. Both the grown volumes and the surfaces can be stored
Appendix B: Selected well logs

Marked-up log Well-3T06

LOGGING DATE: November 4, 2001

COMPLETION:
Open hole: 1196’-1160’ (36’)
Net. Pay: 24’ (in completed interval)
Av. $\Phi$: 38% (in completed interval)
Av. $S_w$: 14% (in completed interval)
Est.: 250 (+/- 20%) bopd

Symbols:

Completion

Sidewall core (oil indication)

TOP T-UNIT 1114’

1130’

1150’

1183’

1187’

TOP CRETAEOUS 1196’

80.00 mV

0.00 GR

API

150.00

1/240

0.20 DFL

ohm-m

2000.00

0.20 HRI MEDIUM

ohm-m

2000.00

0.20 HRI DEEP

ohm-m

2000.00
**Marked-up log Well-3T07**

**LOGGING DATE:** November 9/10, 2001

**COMPLETION:**
- Open hole: 1203'-1160' (43')
- Net Pay: 19' (in completed interval)
- Av. $\Phi$: 35% (in completed interval)
- Av. $S_w$: 28% (in completed interval)
- Est. Prod.: 70 (+/- 20%) bopd

**Symbols:**
- SAND
- CLAY
- CALCAREOUS
- CLAYEY SAND
- SANDY CLAY
- KAOLINITE
- LIGNITE

**Completion:**
- CSP
- PBTD
- PERF.

**Sidewall core (oil indication):**
- GOOD
- FAIR
- POOR
- NONE

**TOP T-UNIT 1120':**
- 1142'
- 1152'
- 1158'
- 1178'
- 1190'

**TOP CRETACEOUS 1205':**
- 1158'
- 1178'
- 1190'

**Properties:**
- **SP (mV):** 80.00 - 180.00
- **API:** 150.00
- **GR:** 1:240
- **DFL:** 0.20
- **API:** 2000.00
- **GR:** 0.20
- **Ohm-m:** HRI MEDIUM 0.00 - 2000.00
- **Ohm-m:** HRI DEEP 0.00 - 2000.00

**Top T-Unit:**
- 1203'

**Top Cretaceous:**
- 1205'

**Completion Details:**
- CSP
- PBTD
Appendix C: Colour figures.
Figure 2.17. 3D seismic survey, which covers large part of the Tambaredjo Oil Field. Interpretation of the top Cretaceous surface and OWC.

Figure 2.25. Example of the acoustic impedance section together with the density logs from wells 3t06, 3t07 and 3t08. The approximate positions of the markers: top Cretaceous (TC) and Hardebank (HB) are indicated.
Figure 3.1. Visualization consisting of four seismic cross-sections from the AI volume, and a volume window through the study dataset, where a channel like object can be recognised (white arrow).

Figure 3.2. Volume window visualization of the acoustic impedance inside a “pizza” box on the left and the histogram panel for changing the colour lookup table on the right.
Figure 3.14. East-West fault system that divides the Tambaredjo field into two parts.

Figure 3.15. T-sand units in the production area 3Q24 with high tectonic activity and several wells drilled. Tectonics influenced the deposition of the sands; the large accommodation space was due to syndepositional faulting in this zone.
Figure 4.1. Cross section of the clustered voxels using the $K$-means algorithm for a number classes equal to seven in the study interval (excluding the Hardebank and Top Cretaceous): a) original AI slice. b) Result of $K$-means clustering based on the AI.

Figure 4.2. Result of an unsupervised classification using the ISODATA algorithm for a minimum number of classes equal to 5 and a maximum equal to 10. The cluster that is visualised can be interpreted as sand, the light colours below can be interpreted as top Cretaceous (TC) and the light colours above as the Hardebank (HB).
Figure 4.3. Resulting map of UVQ segmentation of the data in the reservoir interval into 5 classes applied to the waveform only. Area size: inline range 200 – 875, crossline range 5-875. Used horizon: Hardebank. Time gate [-4, 12] ms. Two channel-like features can be recognised (arrows).
Figure 4.5. Selected area (small rectangle) to perform the experiment in the 3O24 drilling cluster, where the locations of few wells are pinpointed with green vertical lines.

Figure 5.1. Reservoir interval delimited by the two seismic markers Hardebank and top Cretaceous unconformity.
Figure 5.7. Comparison of original AI slice (right), with a slice of the corresponding flattened slice from the GeoTime cube (left). Notice that the values outside of the study interval are set to zero in the GeoTime cube. Horizontal scale indication is approximate.

Figure 6.17. Sand sheet with three wells (white lines), where the logs confirm the presence of a thick sandstone. Notice a part of channel fill deposit in the left side (dotted curve) and a point bar-like feature (arrow) on the right side of the 3D image segment. The distance between the wells is approximately 200m.
About the author

Israel Rivera Rabelo was born in Santa Clara, Cuba on March 3rd 1967. At the age of 16, he came to study nuclear engineering at Czech Technical University in Prague, Czech Republic. After finishing his university study, he started working for the Cuban Geological Survey in 1990. In 1997, he finished a master course in applied computer science at University of Las Villas in Santa Clara, Cuba; and in 1999 he finished a professional master course in Geoinformatics at International Institute for Geo-Information Science and Earth Observation, Enschede, The Netherlands. In 2001, he joined the Department of Geotechnology, faculty of Civil Engineering and Geotechnology, Delft University of Technology, where he worked in 3D recognition and parameterisation of geological objects in high-resolution seismic data. He was responsible for the large scale 3D visualization centre at the Department, and he also was involved in the supervision of Master and Bachelor students. Currently he is working as Senior Geoscientist for dGB Earth Sciences B.V.