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Practice makes perfect

University of Alberta

Advances in Stochastic Surface and Facies Modeling of Deepwater
Depositional Systems

by

Xingquan Zhang

A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Master of Science

Department of Civil and Environmental Engineering

Edmonton, Alberta
Fall 2007

University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **Advances in Stochastic Surface and Facies Modeling of Deepwater Depositional Systems** submitted by **Xingquan Zhang** in partial fulfillment of the requirements for the degree of **Master of Science**.

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Dr. Jose C. Cunha (Examiner)

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Dr. Michael G. Lipsett (Examiner)

Date: _____

To Yuling

Abstract

Traditional geostatistical tools are limited to reproduction of one and two-point statistics. Numerical models of reservoirs are constructed by cell-based techniques or by stochastically placed geometric objects. Stochastic surface-based modeling allows for improved integration of geological information in deepwater clastic turbidite reservoir models. Surface-based methods model stratigraphic layers to fill available accommodation space. Stacking patterns and hierarchies of trends related to sedimentary processes are reproduced by construction.

Deepwater surface-based methods are not mature. This thesis documents new developments such as automatic surface-picks identification, deterministic and stochastic surface placement, global and local base levels modeling, improved hierarchical trend modeling and global and depositional erosion events modeling result in more practical workflows and greater integration of deepwater geologic information. The result is improved numerical reservoir models of deepwater systems and, therefore, an expectation of improved reservoir performance forecasting and management.

Acknowledgements

I would like to thank Professor Clayton V. Deutsch for his support and encouragements. As a senior geologist, I proposed many lay-man ideas as other geologists during my research. Dr. Deutsch led me to the world of Geostatistics. As a new research field, my M.Sc. has been a great learning experience. Without his efforts and help, it is impossible for me to think as a geostatistician now.

I would also like to thank Dr. Michael J. Pyrcz. I had been working on the programs written by him, including Alluvsim, Surfsim, Turbsim and others. I gained much knowledge by reading his source codes.

I appreciate the support of my colleges at Centre for Computational Geostatistics, specifically Dr. Weishan Ren who was another source of new ideas.

I dedicate this thesis to my family for their love and encouragement. My wife, Yuling, and daughter, Angelina, are a tremendous source of joy and stability.

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Chapter 1

Introduction

Depositional systems can be classified as continental depositional systems, coastal and nearshore depositional systems, continental shelf depositional systems and deep-sea depositional systems (DSD) based on their position. Each depositional systems can be further classified (Figure 1-1) in basin scale. Global hydrocarbon resources are unequally distributed in these depositional systems (Figure 1-2). Siliciclastic shoreline systems (SSL) and carbonate shelf systems and reefs (CSR) are the most important hydrocarbon bearing and production depositional systems due to their tectonic positions and proximity to hydrocarbon source locations. Discovered hydrocarbon reserves in deep-sea depositional systems (DSD) accounts for the smallest part of discovered global hydrocarbon resources (Figure 1-3): (1) deep-sea environments were inaccessible to the petroleum industry for many years, and (2) depositional mechanisms are very complicated. There are still many aspects of deepwater depositional systems that are poorly understood until now. Therefore, there are many different geologic "models" for deepwater environment (Stow, 1992). However, with the development of new equipment and techniques, drilling in deeper water area becomes possible. As the result, deepwater environments will be more and more important in hydrocarbon exploration. It will be an important supplement to world hydrocarbon production.

Deepwater turbidite systems have become important exploration targets since the exploration success in 1970s (Stow, 1992; Stelting *et al.*, 2000). Research in deepwater turbidite has been active since then. An accurate geological model is important to minimize the development risk due to the high development costs. The inaccessibility of deepwater environment and complicated spatial structures results in a high degree of uncertainty. Under this situation, stochastic simulation approaches are widely applied in deepwater turbidite reservoir investigation to quantify the uncertainty by building multiple equiprobable realizations.

Conventional stochastic facies, porosity and permeability models are often cell based. These models are generally limited to reproduce one- and two-point statistics, therefore complicated spatial structures cannot be well reproduced (Pyrcz, 2005; Deutsch, 2006). Multiple-point statistics is a good alternative, but actual subsurface data from the field being modeled are rarely enough to allow inference of multiple-point statistics (Strebelle, 2002). The desire to reproduce more geologically realistic models naturally leads to the development of object- or surface-based simulation approaches. Object based techniques were pioneered by Haldorsen and Lake (1984), Haldorsen and Chang (1986) and Stoyan *et al.* (1987). Surface based techniques were introduced

recently (Xie and Deutsch, 2000; Deutsch *et al.*, 2001; Pyrcz and Deutsch, 2003, 2005). Object-and surface-based simulation techniques development has been important targets for many years.
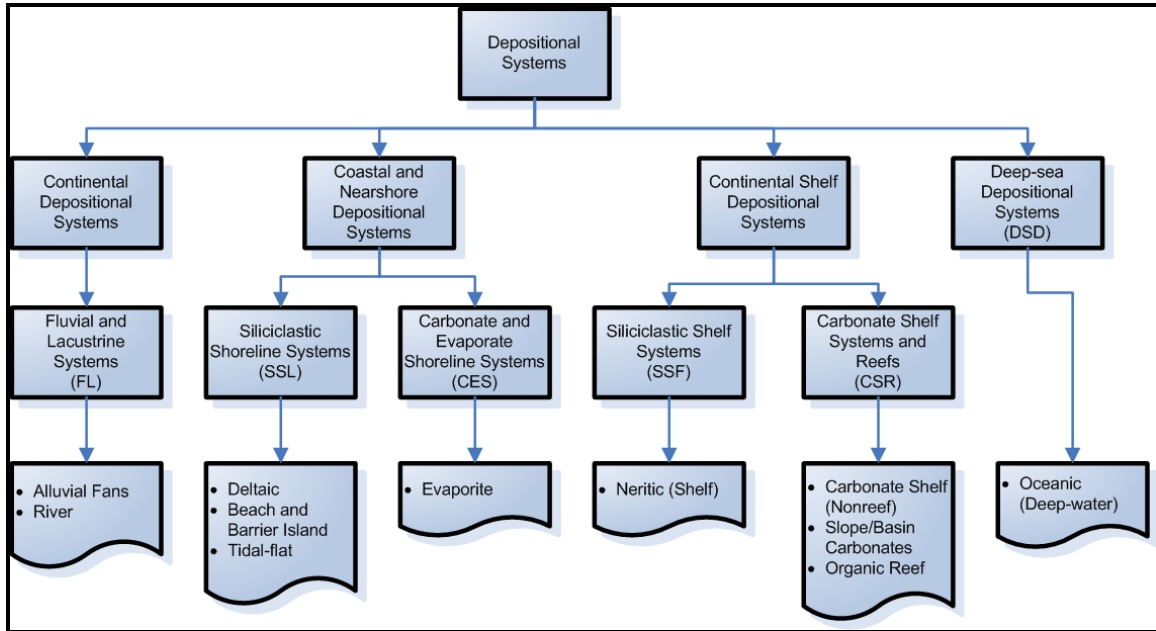
Figure 1-1: A diagram showing the depositional systems classification used in this research (after Boggs, 2001 and Allen *et al.*, 2005)
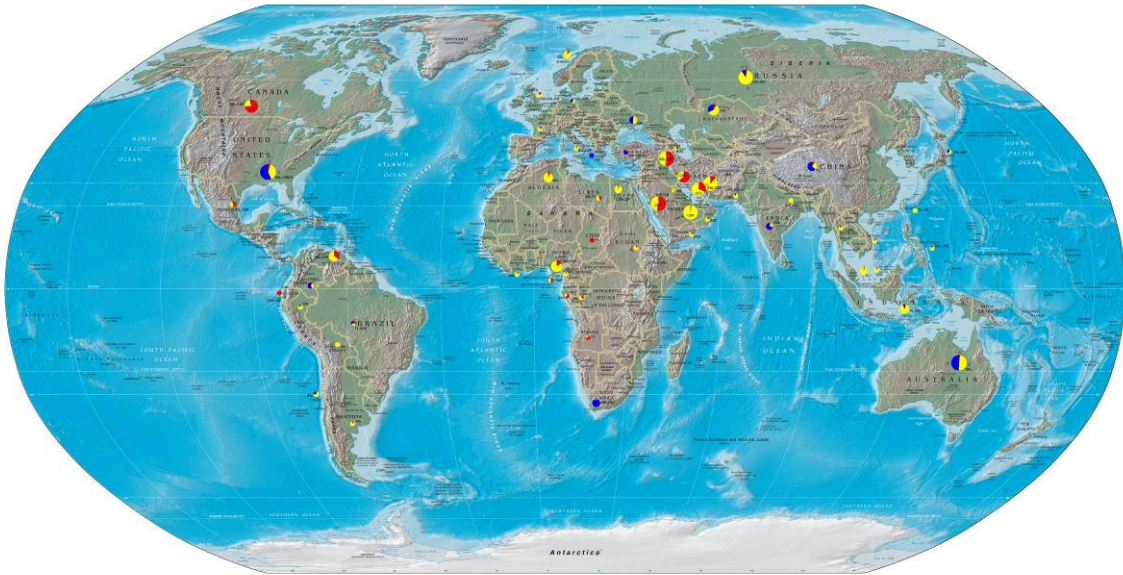
Figure 1-2: The world hydrocarbon resources distribution (data from American Energy Information Administration; until January, 2006). Data are collected on countries and districts basis. The circle size represents the relative importance of that country / district in the world hydrocarbon resources. The red, yellow and blue colors represent oil, gas and coal resources, respectively.
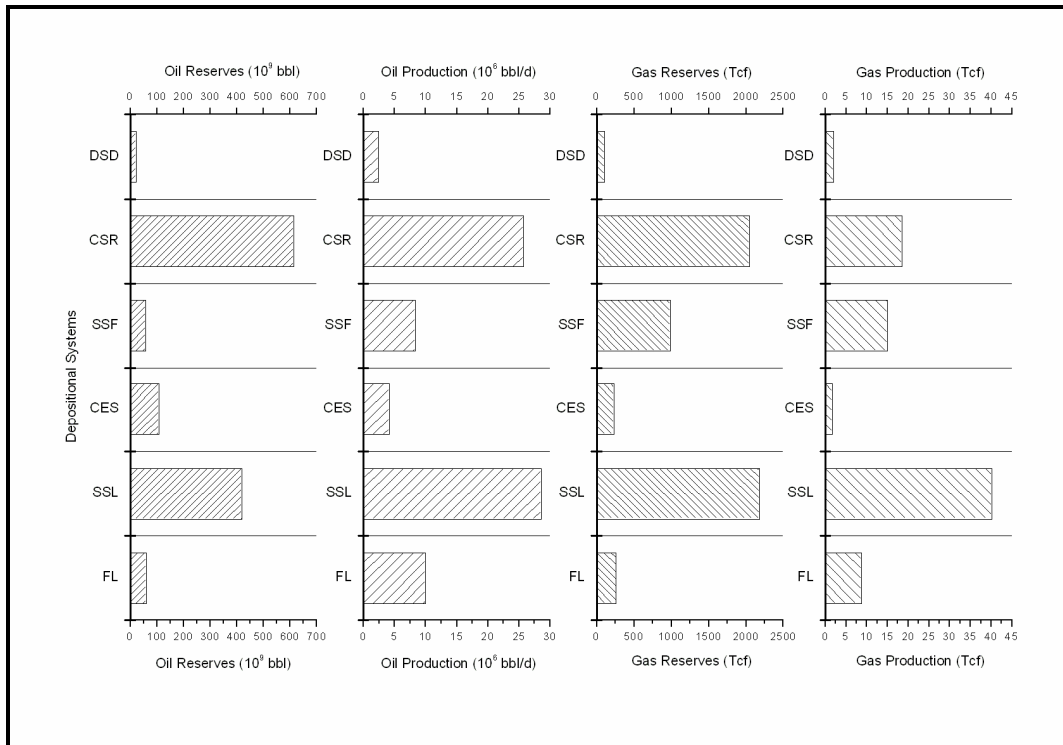
Figure 1-3: The world hydrocarbon resources distribution in different depositional systems.

1.1 Deepwater turbidite modeling

The first version of object-based deepwater turbidite reservoir modeling program is the `Lobe-Sim` program developed by Deutsch and Tran (1999). A "simple" surface template was proposed and followed by later surface-based modeling techniques. This program was based on simulated annealing technique; both surface geometries and facies components can be well honoured, but the algorithm is quite slow.

Xie and Deutsch (2000) proposed the surface-based modeling program, `SurfSim`, which is based on a rule-based scheme to enforce data conditioning. The proposed methodology stochastically builds a surface model and honours available surface picks; rules based on volume filling and types of stratal termination and the reproduction of within unit trends. The generated surface model mimics the appearance of actual geologic bounding surfaces and successfully applied in an outcrop with tabular units.

Pyrcz and Deutsch (2003) proposed a hierarchical surface modeling program, `TurbSim`; models based on user-specified surface geometry parameters. The large-scale geometry may be a third-order lobe or bounding surfaces extracted from seismic. The fine-scale geometry is a second-order lobe. Surface model may be built hierarchically, that is, both large- and small-scale lobes may be built. A rejection algorithm was proposed for well conditioning, but the conver-

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gence may be very slow with many wells. Facies are not simulated directly. As an alternative, a surface-based hierarchical petrophysical trend modeling approach was proposed to simulate reservoir petrophysical properties which follow the modeled reservoir spatial structures.

A limitation of `TurbSim` is that it assumes only single source location for all lobe events within given bounding surfaces. To extend the application of surface-based techniques in common geological settings without modeling third-order lobes firstly, `LE_model` program was designed by Deutsch in 2006. Surfaces extracted from seismic image were applied directly as bounding surfaces and multiple source locations may be specified. Besides the flexibility, the limitations of `LE_model` are also apparent: (1) candidate surfaces are positioned on a datum with the minimum elevation of the former surface within study area, so some surfaces may have very small volumes since much volume is located under former surfaces. The minimum elevation updates much slower than surface stacking rate; therefore, much volume is missed in the later surface modeling stage. A base surface transform method was applied to mitigate volume missing problem, but it did not change the situation much (Figure 1-4). After 75% of filling proportion, more surfaces were needed to fill the remaining volume. (2) the entry position of a candidate surface is randomly picked without any constraints; therefore the simulated surface may not follow local bathymetry very well, and (3) the program is unconditional, that is, it cannot reproduce intersections at local well data.
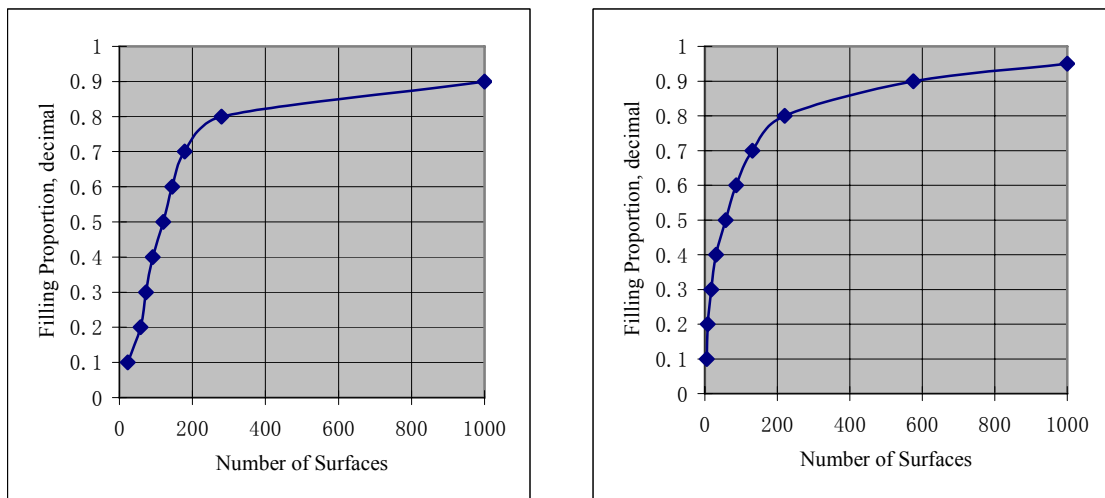
Figure 1-4: the cross plots of number of surfaces and filling proportion. Left: original surface placement rules without base surface transformation; Right: original surface placement rules with flattening base surface.

The research in this thesis is based on the research codes described above. The goal is to develop an algorithm that overcomes many of the limitations that have been identified.

1.2 An introductory example

The geological reality cannot be known with limited data. Therefore, the "truth" will never be known in practice. Figure 1-5 shows an idealized deepwater turbidite model representing a geological truth. The top and base surfaces are tilted and they pinch out towards north and west edges. Such pinch outs are common in continental slope environments. With flow energy diminishing along streamlines, a special facies depositional sequence, the Bouma sequence, may form in a flooding event. In the conceptual model, facies relationship is very strict and clear. In practice, the facies relationship can only be coarsely honoured due to energy fluctuations. 36 wells are regularly sampled in the conceptual model with 1000 meters well distance. The well positions are shown in Figure 1-6 with the corresponding stratigraphic thickness map. In practice, such kind of dense well pattern seldom exists for the high drilling costs in deepwater environments. A cross surface section and the corresponding facies section are shown in Figure 1-7 and Figure 1-8, respectively. Note the lobe thickness diminishes quickly along flow direction. Therefore, the curvilinear shape of facies distribution is very clear and follows the shape of surfaces.

1.2.1 Uncertainty on well correlations

Conventionally, reservoir structure is modeled with a series of well correlation plots and fence diagrams, horizontal facies distribution maps and layer thickness plots. Sections with similar well log characteristics and lithology characteristics are usually grouped in a geological layer. In modern analysis, this is done within a sequence stratigraphic context.

Surface picks identification. Surface picks are the intersections of surfaces / lobes with well trajectories. Each interval between two surface picks is a Bouma sequence. This sequence is usually incomplete in practice due to lateral facies changes and depositional erosional events. Some surface picks with similar depositional characteristics may be grouped as larger-scale depositional unit.

Well correlation maps or fence diagrams plotting. The correlation may be based on surface picks. Building a 3D reservoir structural model by hand is impossible. Descriptive language is used instead of giving a quantitative structure model. With the same identified surface picks, different correlation maps may be plotted based on different geological understandings. In practice, usually only one correlation map is made because the procedure is tedious and time-consuming when large amount of wells are available. Figure 1-9 shows a hand-contoured well correlation map.
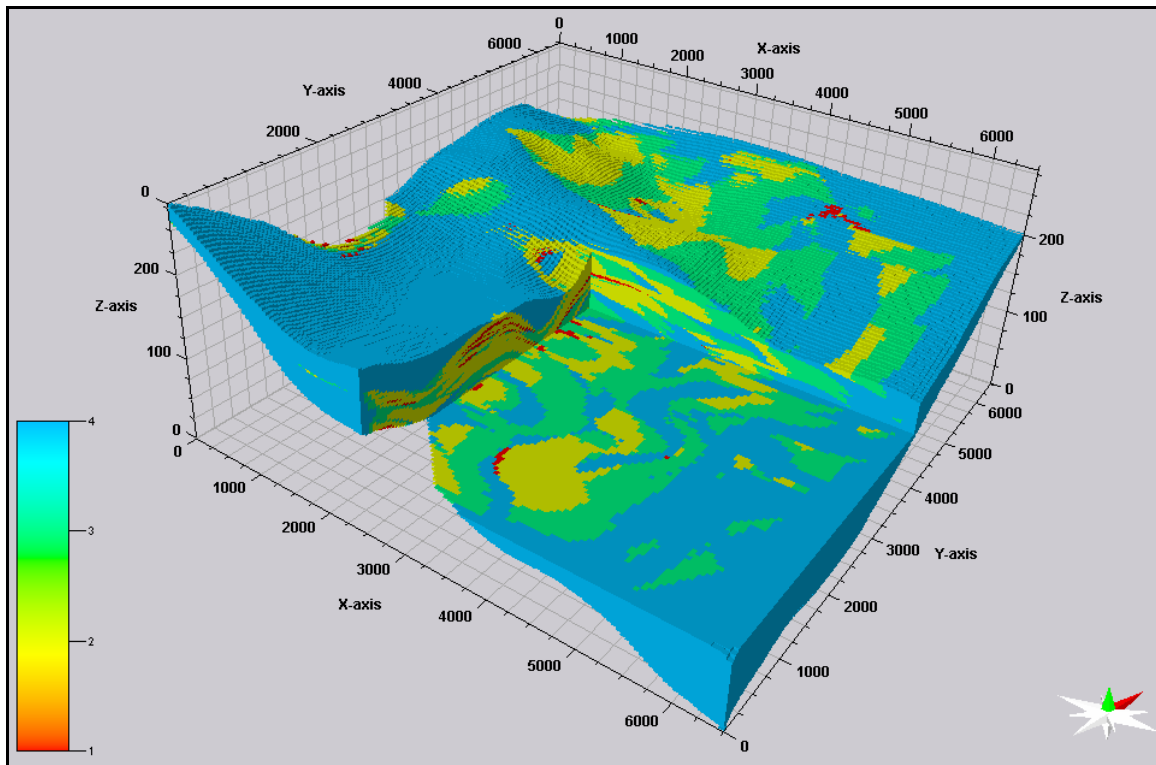
Figure 1-5: A conceptual deepwater turbidite depositional model showing the idealized 3D facies distribution. Note the curvilinear shape in both directions.
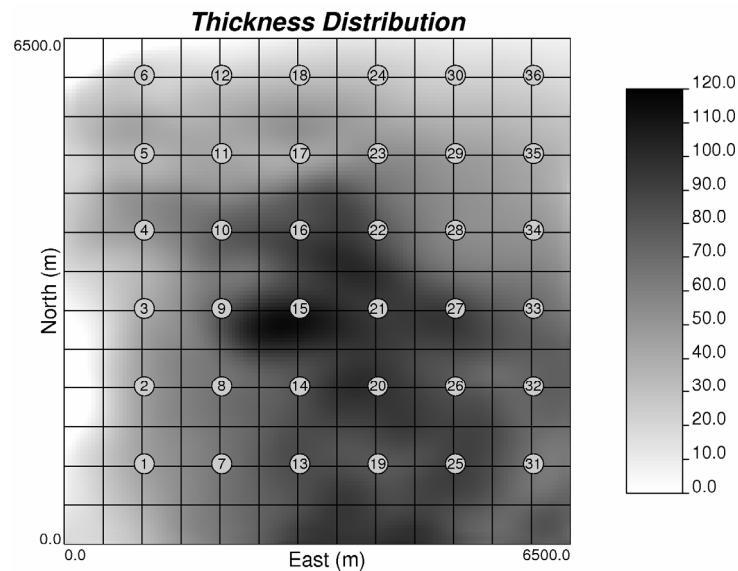
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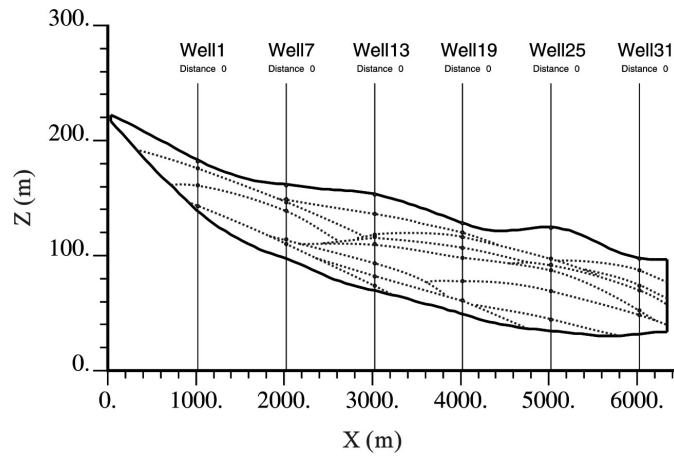
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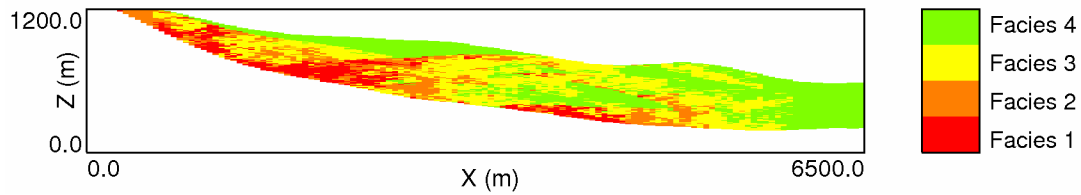
Figure 1-8: A possible facies distribution within the surface model shown in Figure 1-7. The curvilinear shape of the facies model is also very clear and follows the geometry of surface / lobe model.
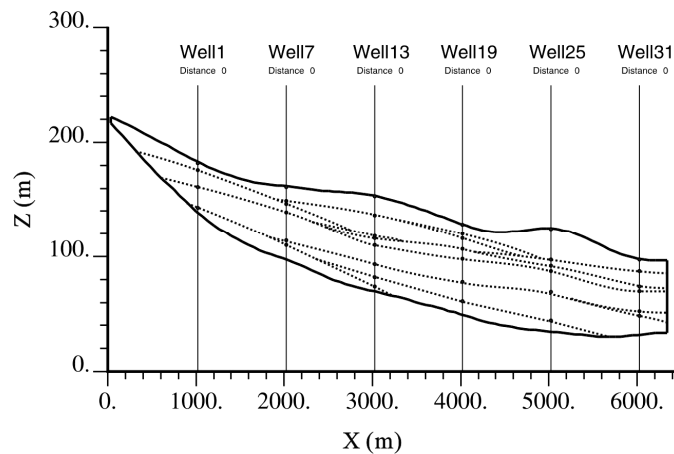
Figure 1-9: The identified surface picks and a hand-contoured well correlation map based on surface picks.

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The limitations of above approach are apparent. The correlation maps are usually built deterministically. The procedure is tedious and time-consuming. It is inefficient to build multiple correlations by hand if large amount of wells exist. The correlation procedure is subjective, which has the advantage of accounting for expert knowledge; however, it is difficult and the scale of identified geological body may be unreasonable if well distance is sparse. When wells are limited, the extrapolation from wells is difficult and ambiguous. In this case, the spatial structure is commonly built at large-scale. Several Bouma sequences may be grouped together as a unit. Each unit is equivalent to a second-order lobe. The curvilinear shape of lobes is awkward to map by hand. Therefore, the result may look more like a "layer-cake" model and the spatial continuity inference may be incorrect.

Sequence stratigraphy may be applied to guide consistent reservoir structure building. In large-scale and when seismic data are available, the stratigraphic framework building is relatively straightforward. However, the resolution of seismic data is usually not good enough for fine-scale structure identification. Therefore, the solution for fine-scale reservoir structure model may not be unique.

In a word, lacking of control results in great uncertainty on fine-scale reservoir structure construction / modeling, which cannot be quantified by conventional approaches.

1.2.2 Uncertainty on facies distribution

The distribution of facies controls the distribution of petrophysical rock properties, such as porosity and permeability. Therefore, the prediction of facies distribution is an important topic in reservoir modeling. Large-scale facies distribution may be visualized on high-resolution seismic image. However, fine-scale facies can only be identified on wells and outcrops, which cannot be continuously traced on seismic. 2D mapping methodologies are applied often to map areal facies distributions, such as kriging methods and minimum curvature method. These maps are deterministic and they are the average of a layer. Therefore, they are only trend maps and cannot be used to quantify the uncertainty of a specific location. Another type of facies trend map is hand-contoured conceptual facies model (Figure 1-10).

Hand contoured facies models are deterministic and therefore uncertainty is not quantified. Cell-based stochastic modeling techniques may be applied to quantify the uncertainty of facies distribution. The major limitation of cell-based facies modeling techniques is that only one- and two-point statistics can be reproduced, so the complicated reservoir structure cannot be captured. Figure 1-11 shows a typical SIS-based facies cross section based on the 36 wells data. Although there are plenty of wells and average well distance is only 1 kilometre, the curvilinear shape of facies still cannot be well reproduced. In this research, a depositional trend-based facies modeling

method is proposed. The method is also cell-based. The depositional coordinate of each cell is calculated and facies proportions are calculated based on specified trend template. Depositional coordinate is the relative position in specific lobe. Therefore, continuous surface information is transformed to discrete cell-based facies proportions information, which can be integrated by many SIS-based facies modeling techniques, such as truncated Gaussian simulation (GTSIM), blocked sequential indicator simulation (BlockSIS) and sequential indicator simulation with local means (sisim_lm).

In a word, uncertainty of facies distribution results from (1) the uncertainty of fine-scale reservoir structures and (2) the uncertainty of cell-based facies modeling methodologies.
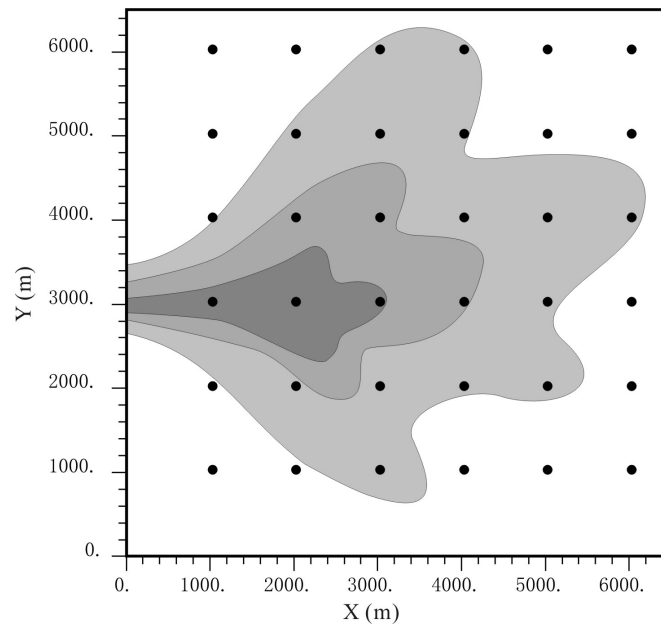
Figure 1-10: A possible hand-contoured facies distribution based on wells data and well correlation.
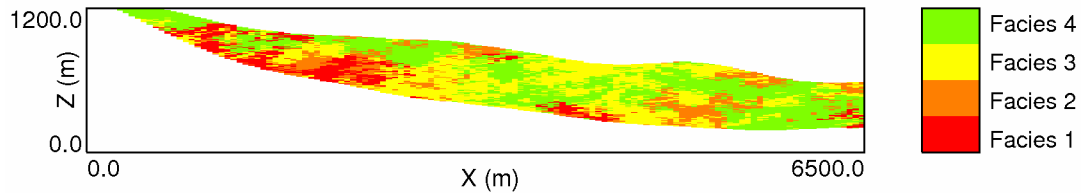
Figure 1-11: A conventional SIS-based facies section based on wells data. Although there are many wells available, the spatial structure is not realistic and does not follow the shape of the conceptual depositional model.

1.3 Dissertation outline

Chapter 2 is an overview of the geological background of deepwater depositional systems. Section 2.1 reviews deep sea environments. Section 2.2 illustrates the deepwater turbidite classification used in this thesis and their major characteristics. Section 2.3 illustrates the major components of turbidity current. Section 2.4 presents the idealized vertical profile, Bouma sequence, and its characteristic of each division. Section 2.5 discusses the large-scale controlling parameters on turbidite distribution.

Chapter 3 illustrates advances in surface based modeling made in this research. Section 3.1 presents an automatic procedure for surface identification based on well logs. Section 3.2 presents advances in lobe events modeling. Section 3.3 illustrates the advances on strataform surface simulation.

Chapter 4 demonstrates a possible application of constructed facies models and the surface-based facies modeling approach. Section 4.1 introduces the conceptual turbidite model used in this thesis. Section 4.2 presents how to integrate vertical facies trends with conceptual facies model (idealized areal facies distribution). Section 4.3 illustrates how to integrate statistical trends and how to honour global facies proportions. Section 4.4 illustrates two cell-based facies modeling approaches with integrating facies proportions information. Section 4.5 presents a geologically realistic case study to present the application of surface-base modeling approach.

Chapter 5 presents a turbidite case study example. A statistical workflow is presented. The reservoir is located in a typical deepwater environment with 36 synthetic wells. Known conditioning data include surface picks, facies, porosity and permeability. 25 stochastic surface models are built with honouring all surface picks. All available facies, porosity and permeability data are honoured in coming reservoir properties modeling stage.

Chapter 6 presents conclusions and discusses the limitations of the research.

Chapter 2

Geological Background

There are three fundamental deepwater depositional environments, (1) slope aprons, (2) submarine fans, and (3) basin plains. Second-order turbidite lobe focus of this thesis is an important component of deepwater submarine fans. The chief characteristics of deepwater submarine fans are illustrated in this chapter, (1) a brief introduction of deep sea environment, (2) the classification and basic characteristics of deepwater submarine fans, (3) major components of large-scale turbidity current, (4) components of idealized vertical profile, the Bouma sequence, and (5) major controlling parameters on the morphology of deepwater depositional systems.

2.1 Deep sea environment

The deep sea can be subdivided into several topographical units, (1) deep-sea grabens, (2) ocean basins, and (3) continental margins. Most submarine fans are located along continental margins. The bottom gradient of typical submarine fans is usually less than 0.5 degrees (Table 2-1). Submarine canyons play an important role in carrying large amount of sediments across continental margins to form submarine fans. These canyons and channels are easily visualized on high resolution seismic image.

Location	Bottom gradient in degrees
Submarine canyons	1.0 – 3.0
Upper fan channels	0.2 – 0.5
Middle fan lobes	0.1 – 0.4
Lower fan	0.1 – 0.2

Table 2-1: Typical gradients of submarine fans (after Pickering *et al.* 1989)

Reineck and Singh (1980) summarized the important transport systems in the continental shelf, margin and ocean basins, which produce characteristic types of deep-sea deposits:

1) Fluvial mixed transport and separation of sand and lutum.
2) Transport and deposition of sand, including longshore transport and canyon and distributary transport.
3) Low-velocity, low-density turbidity currents.
4) High-velocity, high-density turbidity currents.
5) Sediment slides of larger dimensions.
6) Transport through contour currents.

Transport systems of deep sea environment are complicated; therefore, a universal process-based turbidite modeling program is impractical.

Although the transport mechanisms are different, many transport systems form similar deposition structures. Middleton and Hampton (1976) distinguished four types of sediment gravity flow and their possible deposition forms:

1) Turbidity current flow → turbidite.
2) Liquefied sediment flow → turbidite.
3) Grain flow → resedimented conglomerate and some fluxo turbidite.
4) Debris flow → pebbly mudstone.

Therefore, surface-based modeling technique is more practical by neglecting specific depositional mechanisms and modeling lobe geometry instead. As a geometry-based simulation approach, surface-based modeling technique may be applied in many types of turbidite depositional systems with similar spatial structures.

2.2 Deepwater turbidite classification

Each turbidite system has unique tectonic setting, sediment supply and oceanographic controls (Stow, 1992). For simplicity, an idealized end-member classification is applied in this research. There are two types of deepwater submarine fans, radial fan and elongate fan. Radial fan includes three regions, upper fan, mid-fan and lower fan. Upper fan region is dominated by a single feeder channel or canyon that is flanked by distinct levees; mid-fan region is characterized by distributory channels and depositional lobes; lower fan is smooth with low-gradient. Radial fans are usually sand-rich. Elongate fans extend longitudinally away from a relatively broad head region, either perpendicular to or sub-parallel to the source-area margin. Two or more main fan channels may be developed with distinct confined levees and these channels meander across an extensive mid-fan area. Large terminal lobes form in smooth lower fan region. The facies distribution is more elongate than concentric. These fans are often referred to as mud-rich fans. The research in this thesis focuses on second-order lobes, which may be middle fan lobes of a radial fan or distal fan lobes of an elongate fan.

The classification of smaller-scale architectural elements of turbidite environment is also complicated. Many classifications were proposed for specific research purposes or based on different geological settings. For example, the Reading and Richards (1984) scheme was based on grain size and feeder system and it was proposed to describe various architectural element associations. The Ghosh and Lowe (1993) scheme, a hierarchical process-based architectural elements classification scheme, is applied in this research. According to this classification, individual homogene-

ous components are identified as first-order architectural elements, including individual division of the Bouma sequence and other coarser components. A single or collections of first-order elements forms a second-order element, which represents products of a flow event. Third- and fourth-order architectural elements represent reservoir-scale features, such as lobes and channel-levee systems. These elements can be visualized and continuously traced on high-resolution seismic, so they are treated as boundary conditions in this research. Note that because of the resolution of seismic, these bounding surfaces may have some uncertainty.

2.3 Components of large-scale turbidity current

As mentioned above, turbidity current is an important transport system in deepwater environment. Small-scale turbidity currents have great variability. Large-scale turbidity current may be distinguished into head, body and tail components (Figure 2-1). Head is the thickest part and the region of erosion and formation of scour marks; body is rather uniform in thickness through its length; and tail is where flow thins out and becomes dilute. Dense medium (sediment-water mixture) must be continuously supplied in the head to compensate for the losses caused by the turbulences (Middleton and Hampton, 1976). If loss is larger than compensation, the turbidity current slows down and begins forming a new lobe.
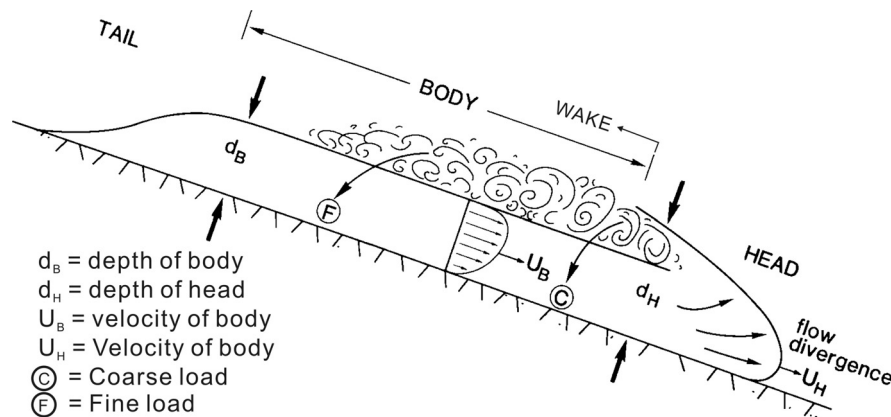
Figure 2-1: Simplified sketch of a large turbidity current, divided into head, body and tail regions. Setting from the wake behind the head produces a lateral size grading in the flow (after Pickering *et al*. 1989).

2.4 Components of Bouma sequence

Bouma (1962) made a comprehensive study of ancient turbidites and developed a vertical facies model, the well-known Bouma sequence (Figure 2-2). An idealized turbidite sequence is made up of five divisions with specific sedimentary structures:

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1) **Graded interval**, the lowest part. It shows more or less distinct graded bedding. No other sedimentary structures exist. It is sandy or gravelly in nature. The contact to the former deposition is usually erosional.

2) **Lower interval of parallel lamination**. It shows predominantly thick parallel laminae of sand. The contact to the graded interval is gradual.

3) **Current ripple lamination interval**. It is made up of fine sand and silty sediments and shows small-current ripple bedding. An indistinct grading is present from bottom to top.

4) **Upper interval of parallel lamination**. It is a very fine sandy to silty clay zone showing a distinct parallel lamination.

5) **Pelitic interval**. This is a clayey sediments interval. No distinct sedimentary structures exist.

These intervals are seldom completely observed due to lateral facies change and depositional erosions. Note that Bouma sequence is idealized. Many researchers modified it based on geological settings, such as Hesse (1992), Pickering (1989).

Figure 2-2: Modified Bouma sequence of primary sedimentary structures in an ideal turbidite showing a pelagic (or hemipelagic) interturbidite layer (F-division) separated from the pelitic E-division (after Pickering *et al*. 1989).

2.5 Large-scale controlling parameters on turbidite morphology

The natural development of surface models involves geological processes that occur over a range of time-scales. Stow *et al.* (1996) and Baas *et al.* (2005) summarized the major long-scale parameters controlling the morphology of deep-water depositional systems (Table 2-1). In general, the shape and internal organization of deep-water systems vary as a function of grain size, sea-level, basin configuration and degree of basin confinement, number and distribution of sediment

input points and tectonic setting. Grain size represents flow energy which controls the lobe geometry and scale, such as lobe shape, length and width. In `LE_model` program developed in this thesis, lobe geometries are randomly drawn from user specified distributions. From Figure 2-2, it is very clear that turbidite flow events are driven by processes on annual or sub-annual time-scale. Therefore, long-scale controlling parameters, such as sea-level changes, basin configuration, degree of basin confinement and tectonic settings are assumed stable during stochastic lobe events modeling. In particular, sea-level changes result in different surface stacking patterns, such as aggradation, progradation and retrogradation, and large-scale thickness trend. The number and distribution of sediment input points can be specified explicitly in `LE_model` program. The sediment input points are located on one edge of the model. A coordinate transform could be applied to rotate the spatial coordinates to align the model with the paleocurrent.

Long-scale controlling parameters	Short-scale controlling parameters
Regional basin tectonics	Local tectonics
	Basin bathymetry
	Basin and basin margin geometry
	Entry point distribution
Sea-level fluctuations	Eustatic changes
	Tectonically induced changes
	Variations in clastic input
Rate, type and source of sediment supply	Depositional process
	Hinterland type and climate
	Nearshore system, type and shape
	Shelf systems, type and shape

Table 2-1 Major parameters controlling the morphology of deepwater clastic depositional systems (after Baas *et al.* 2005)

Chapter 3

Advances in Surface Based Modeling

The research in this thesis focuses on two modeling targets, (1) second-order lobes, and (2) strataform surfaces. Lobe events modeling is mainly based on the `LE_model` and `TurbSim` programs. Strataform modeling is based on the `Surfsim` program developed by Pyrcz in 2004.

Section 3.1 illustrates an automatic surface picks identification approach that can be used as data preparation process for surface modeling; Section 3.2 illustrates advances in lobe event modeling; Section 3.3 presents advances in strataform modeling that make it more flexible and powerful.

3.1 Automatic surface picks identification

Surface picks are the intersections of surfaces with wells. Third-order surfaces can be clearly visualized on high-resolution seismic, but identification of second-order surface picks is problematic. Due to the scale, second-order surface picks can only be identified on well logs, core and outcrops. In general, there is no directly relevant outcrop data to a particular deepwater reservoir. Core is limited due to cost. Therefore, well logs are the common information used for surface picks identification. Experienced geologists can identify them with specific well logs, such as the *RT* (resistivity), *Gr* (Gamma) and / or *SP* (spontaneous potential). In many cases, the accessible logs are interpreted petrophysical property logs instead of raw logs. These logs may be facies proportions, *Fac*(z), porosity, $\phi(z)$, and shale content, *Vsh*(z). The proposed methodology can be applied to raw or interpreted log, and it can be easily modified to utilize multiple well logs to minimize misidentification.

Commonly, bed thickness within a turbidite lobe presents a thinning-upward trend. There are two types of idealized sequence with thinning-upward trend, (1) gradual and progressive thinning-upward trend, and (2) step-like thinning-upward trend (Figure 3-1). The probability of gradual and progressive thinning-upward trends is very small (Pickering, 1989). The proposed approach can handle both trends.

A core profile of the Cumberland Bay Formation (CBF) of South Georgia is selected to illustrate the proposed methodology (Figure 3-2). CBF is a thick sequence of turbidite sandstones deposited in a linear back-arc basin (MacDonald, 1992). The selected profile is a shale abundant vertical sequence located in distal turbidite. A synthetic porosity curve is constructed that is shown as the solid line in Figure 3-3. Lamination information is discarded and only lithofacies

information is kept. Texture information may be important in surface picks identification, how-ever, it is very hard to obtain directly from well logs. Two lithofacies are assumed based on origi-nal profile, sandstone and mudstone.
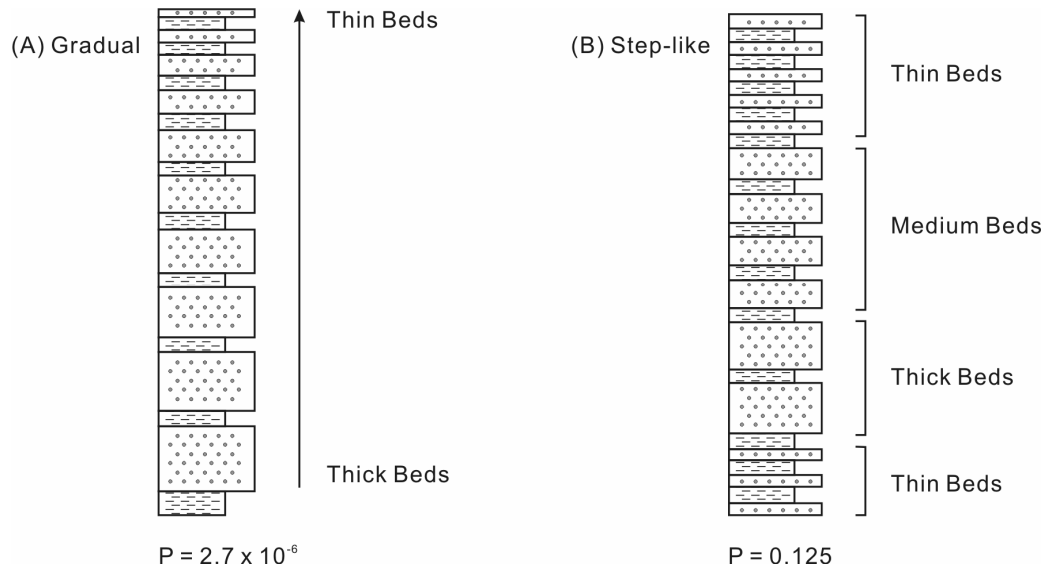
Figure 3-1: Idealized types of sequence (shown as thinning-upward trends, (a) gradual, and (b) step-like (Pickering *et al*. 1989).
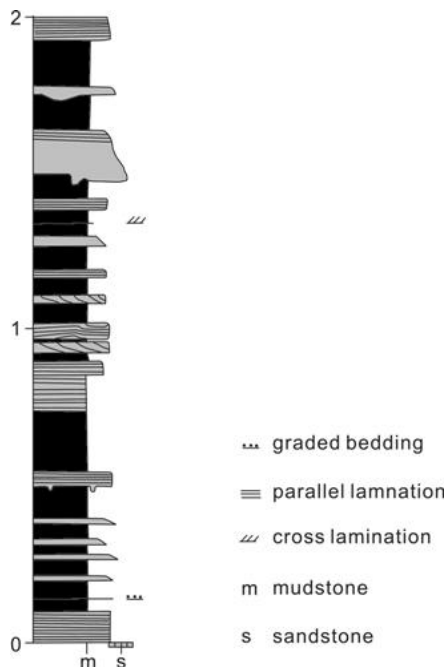
Figure 3-2: A representative sedimentological profile of the Cumberland Bay Formation (CBF) of South Georgia (after, MacDonald, 1992).

graded bedding
parallel lamnation
cross lamination
m mudstone
s sandstone
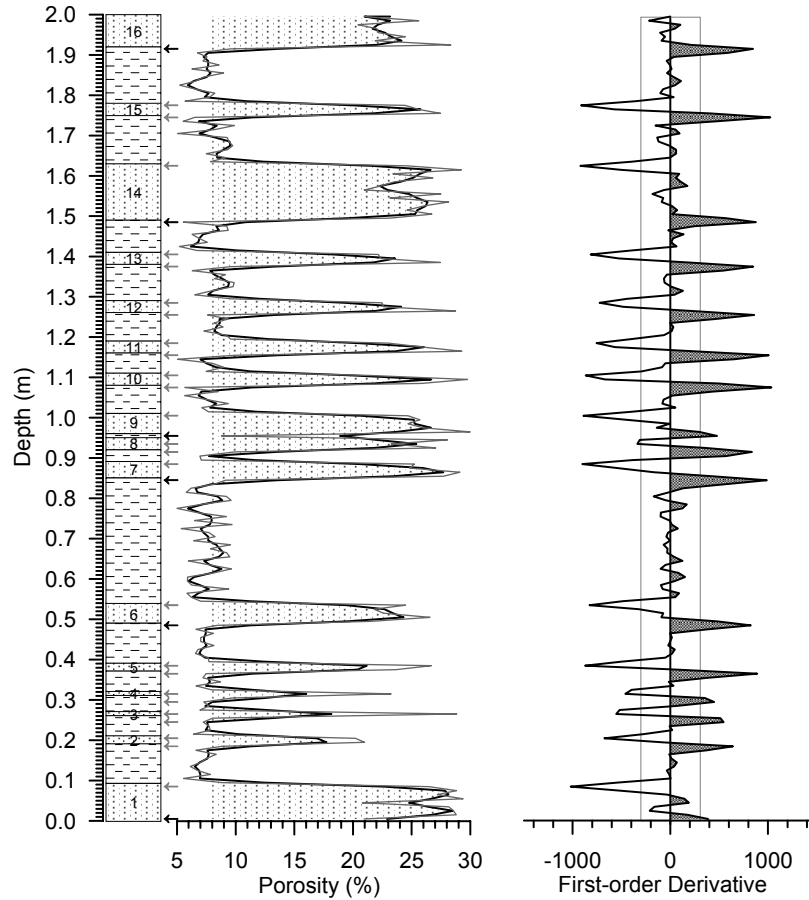
Figure 3-3: A diagram illustrating the vertical lithofacies profile, synthetic porosity curve and auto surface pick identification results. Reference profile is plotted on the left with 16 sandstone layers. The identified rock type picks are shown with gray left arrows, and the identified surface picks are illustrated with dark left arrows. The original porosity is plotted with thin solid line, and the smoothed porosity is illustrated with heavy solid line. High porosity (> 8%) is filled for highlighting. The positive first-order derivative of porosity is also highlighted.

3.1.1 Rock type picks identification

The first step in automatic surface picks identification is rock type picks identification. The identification is based on the fact that effective porosity in sandstone is generally higher than that in mudstone. Therefore, porosity has steeper slope on sandstone boundary. The transition will be very clear if silty deposition is clean.

a. Smooth original curves

Usually, short-scale variability exists within all rock types. It may lead to miss-identification. Therefore, a smoothing approach is implemented as a preprocessor. A simple solution is to smooth the original well log with moving windows. To retain the major curve characteristics, an unequal-weighted moving window smooth methodology is applied.

The method can be expressed as:

$$a_1' = 0.5 \cdot a_1 + 0.25 \cdot (a_0 + a_2)$$ (3.1)

where a_1 is the currently processed value, a_1' is the smoothed value, a_0 and a_2 are the adjacent values. The smoothed porosity curve is plotted as the heavy solid line in Figure 3-3. Alternative smoothing algorithms or different window sizes could be considered if the resulting picks are too frequent or appear to be missed.

b. Rock type picks identification

Rock type picks identification is based on sandstone having higher porosity values and there being a significant rate of change in porosity at a boundary.

First-order derivative of the smoothed curve is calculated to quantify the rate of change:

$$a_0' = (a_1 - a_0)/(d_1 - d_0)$$ (3.2)

where a_0 is the currently processed data point, a_0' is its first-order derivative value, a_1 is the data value of the upper adjacent position, d_0 and d_1 are the depth of a_0 and a_1, respectively. In practice, petrophysical properties are usually interpreted from well logs which are equally sampled, so $d_1 - d_0$ is usually constant. This procedure may be repeated for several times for smoother curve. There are other numerical schemes to calculate the derivative of regularly spaced data; however, this simple approach is considered adequate in most cases.

The lower sandstone boundary has a positive derivative, and upper boundary has a negative derivative (the right plot of Figure 3-3). Lower and upper cutoffs of the derivatives can be specified to identify the surface picks. In the case study, -300.0 and 300.0 are selected, respectively. All 16 sandstone picks are accurately identified (Figure 3-3). There will always be a need for the geological modeler to tune these thresholds and other calculation parameters to attain surface picks that match their interpretation.

3.1.2 Surface picks identification

The proposed methodology is based on identifying thinning-upward depositional trend. Because of flow energy fluctuations, grain size and thickness fluctuation are inevitable. Therefore, an un-equal-weighted moving-window smoothing approach may be applied to eliminate the fluctuations. A drawback of the smoothing is that a thicker sequence may screen adjacent thinner sequences. The modeler has to make the decision on what smoothing to apply. Trial-and-error is required. The thickness distribution of the case study is shown on the left plot in Figure 3-4. The first-order derivative of the example described above is shown on the right plot in Figure 3-4.
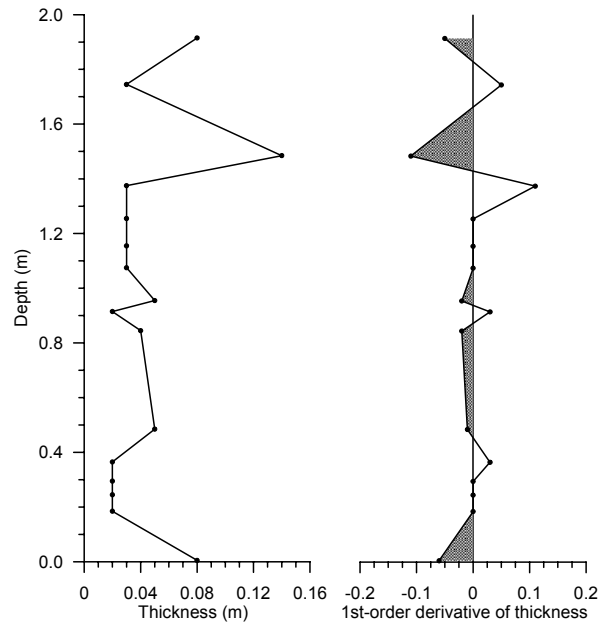
Figure 3-4: Thickness curve and first-order thickness derivative curve. First-order derivatives with negative values are highlighted on the map the show the identified surface picks. The picks are denoted as black left arrows in Figure 3-3.

3.1.3 An example parameter file

A Fortran 90 program, SB_pick, was written to perform the calculations described above. An example parameter file (following GSLIB conventions) is shown below. An explanation of each parameter is provided in Table 3-1.

```
Parameters for SB_pick:

1. por.dat                - file with property values
2. 3        5             - depth column, property column
3. smooth.out             - file with smoothed property & derivative
4. pick.out               - file with surface picks
5. -500.       500.       - lower and upper cutoff of derivatives
6. 0                      - smooth thickness? (0=no,1=yes)
```

Line	Description
1	Input file with property values.
2	Column numbers for depth and proper curve.
3	Output file with smoothed property values and its derivatives.
4	Output file with identified surface picks.
5	Lower and upper cutoff of derivatives.
6	Indicator for performing thickness smoothing or not, 0 = no, 1 = yes.

Table 3-1: A description of the SB_pick parameter file.

3.1.4 Some comments on `SB_pick`

1. In practice, $\phi(z)$ is a function of grain size, sorting and diagenesis. Therefore, porosity may not be a good indicator for surface picks identification. *Fac(z)* and *Vsh(z)* may have better geological response than $\phi(z)$. Some raw well logs such as *RT, Gr* and *SP* may also be used. *SP* log may indicate permeability changes and may be a good sand/shale indicator.

2. The cutoff of first-order derivative of porosity should be adjusted in different problem settings. If the cutoff is set too large, some thinner layers may not be identified.

3. The analysis should be performed separately within each stratigraphic layer.

3.2 Advances in Lobe Events Modeling

3.2.1 Surface Template

During modeling, surfaces are stochastically generated based on a proposed analytical surface template. A simplified lobe geometric template defines the idealized surface shape.

In plan view, the lobe boundary is defined by,

$$W(x) = 4 \cdot wmax \cdot \left(1 - \frac{x}{length}\right)^b \cdot \left[1 - \left(1 - \frac{x}{length}\right)^b\right] \tag{3.3}$$

where $W(x)$ is the width from the centerline, x is the distance along centerline, *wmax* is the maximum width, *length* is the lobe length, a is the relative position of maximum width, and $b = -Ln(2)/Ln(1-a)$ (Figure 3-5).

The lobe geometry is quantified by a gridded surface of thickness. The thickness determination methodology adopted from the channel cross-section geometry determination methodology developed by Deutsch and Wang (1996). Long-section thickness distribution is quantified first; cross-section thickness is determined based on the thickness at centerline location.

Long-section thickness is defined geometrically by,

$$t(x) = 4 \cdot tmax \cdot \left(1 - \frac{x}{length}\right)^b \cdot \left[1 - \left(1 - \frac{x}{length}\right)^b\right] \tag{3.4}$$

where $t(x)$ is the thickness along centerline, *tmax* is the position of maximum thickness, and $b = -Ln(2)/Ln(1-a)$.

Cross-section geometry is defined geometrically by,

$$t(y) = 4 \cdot t(x) \cdot \left(\frac{y}{W(x)}\right)^b \cdot \left[1 - \left(\frac{y}{W(x)}\right)^b\right] \tag{3.5}$$

where $t(y)$ is the thickness along a cross section, y is the distance perpendicular to centerline, $y \in [0, W(x)]$, a is the relative position of maximum thickness, and $b = -Ln(2)/Ln(a)$.

During simulation, *length*, *wmax* and *tmax* are drawn from user-specified distributions; a is deterministic, which is 0.66 in Equations (3.3) and (3.4) and 0.5 in Equation (3.5), which means that the position of maximum width is at 2/3 of lobe length and the geometry of cross sections is symmetric (Figure 3-6).

No channels are constructed and the starting width of a lobe is zero. The centerline of lobe is constructed by lobe width, instead of by local maximum gradient direction. Therefore, the centerline may not be consistent with local maximum gradient.

There is no unique way for object-based lobe parameterization. Surface shape may be modified to fit specific geologic settings. The parameterization could easily get more elaborate at the cost of additional parameters that must be inferred from limited observational data. For example, ruguosity or inter-fingering may be added to the lobe geometry.
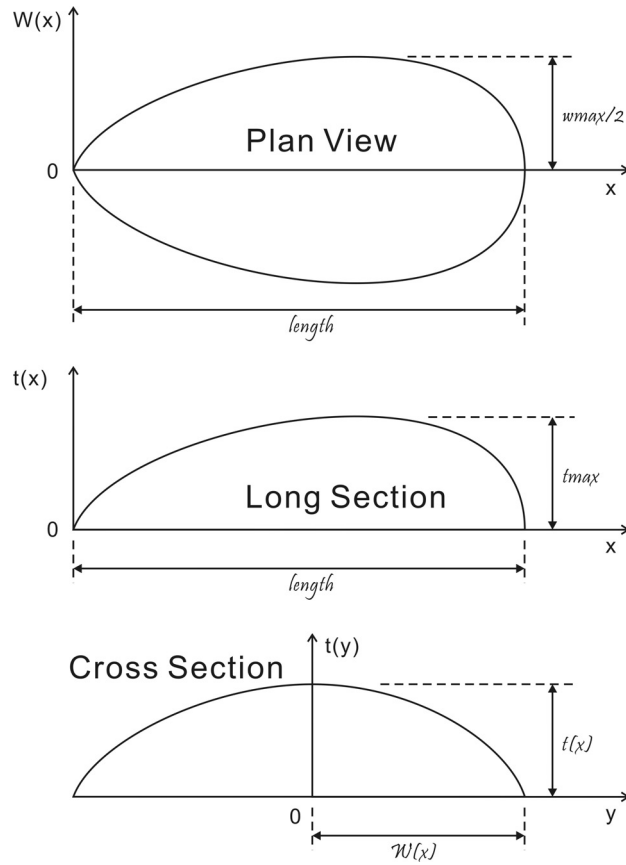
Figure 3-5: Parameters needed to describe the 3-D lobe geometry.
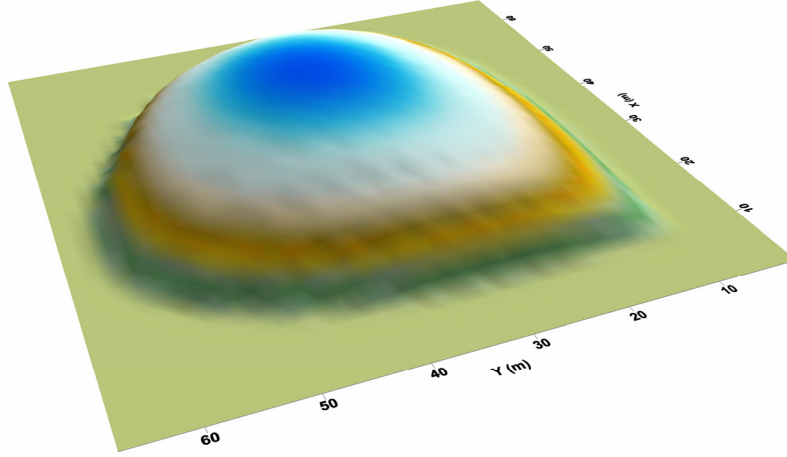
Figure 3-6: A lobe built with proposed analytical surface templates.

3.2.2 Initial Bathymetry

As a gravity-driven mass flow, the shape and orientation of turbidite are strongly controlled by sea floor bathymetry. The initial base surface bathymetry is an important control on the surface evolution procedure. However, paleobathymetry is difficult to infer, especially in the presence of complicated tectonic history. Basin modeling or tectonic inversion based on seismic data and reasonable assumptions may be used. When no information is available to make reasonable assumptions, a simple surface simulation / transformation approach may be applied to rebuild the idealized initial base surface bathymetry. Three base surface transform approaches are applied in `LE_model` program.

1) Flatten base surface

The simplest solution is to flatten the base surface. The transformed stratigraphic coordinate can be expressed as (Deutsch, 2002):

$$z_{rel} = \frac{z - z_{cb}}{z_{ct} - z_{cb}} \tag{3.6}$$

where z_{rel} is the relative stratigraphic coordinate, z_{cb} is the elevation of base level, z_{ct} is the elevation of top surface. The coordinate z_{rel} is 0.0 at stratigraphic base and thickness at stratigraphic top.

This transform may be reversed by:

$$z = z_{cb} + \frac{z_{rel}}{T} \cdot (z_{ct} - z_{cb}) \tag{3.7}$$

This transform is not recommended when there is additional information on the reservoir thickness and geometry.

2) Transform base surface to a paraboloid

The base surface may be transformed to an idealized shape based on global base surface bathymetry. The transformed base surface works as a trend surface that removes high frequency and possible unreliable noise in the bathymetry.

The proposed method is to approximate the base surface by an analytical surface of second order:

$$z = ax^2 + bxy + cy^2 + dx + ey + f \qquad (3.8)$$

The coefficients of the paraboloid are obtained by least-squares solution of an over-determined system of linear equations, given the coordinates of a set of points in the neighborhood of the point of interest:

$$\mathbf{XA^T} = z \qquad (3.9)$$

where $\mathbf{A} = [a, b, c, d, e, f]$ are the parameters of the paraboloid; $\mathbf{X} = [x, y, z]$ are the coordinates of a surface point; and $z = [z_1, z_2, \cdots, z_n]$ are the elevations of base surface (after Krsek *et al.* 1998).

The stratigraphic coordinates are transformed based on the difference between the base level and the fitted paraboloid. That is,

$$z_{rel} = z - (z_{cb} - z_{parab}) \qquad (3.10)$$

where z_{parab} is the elevation of the fitted paraboloid.

This transform may be reversed by:

$$z = z_{rel} + z_{cb} - z_{parab} \qquad (3.11)$$

3) Transform base surface to an incline

When the paleogeometry is approximately linear an incline may be more suitable for simulating the idealized base surface. The analytic surface of first order is expressed as:

$$z = ax + by + c \qquad (3.12)$$

The incline transform and back transform procedures are very similar to the paraboloid transform.

The paraboloid or incline base surface transform are recommended because: (1) the global bathymetry is kept after transform, (2) resulting surface models are more realistic, and (3) honouring stacking patterns becomes possible. The stratigraphic framework is always tilted in deep-water turbidite environments, although the gradient may be very low in the mid-fan area. Empirical studies with the research code have shown that paraboloid and incline transforms are stable in common geological settings, even in high gradient environments, and the resulting surface model is geologically realistic and free from visual artifacts.

(a)
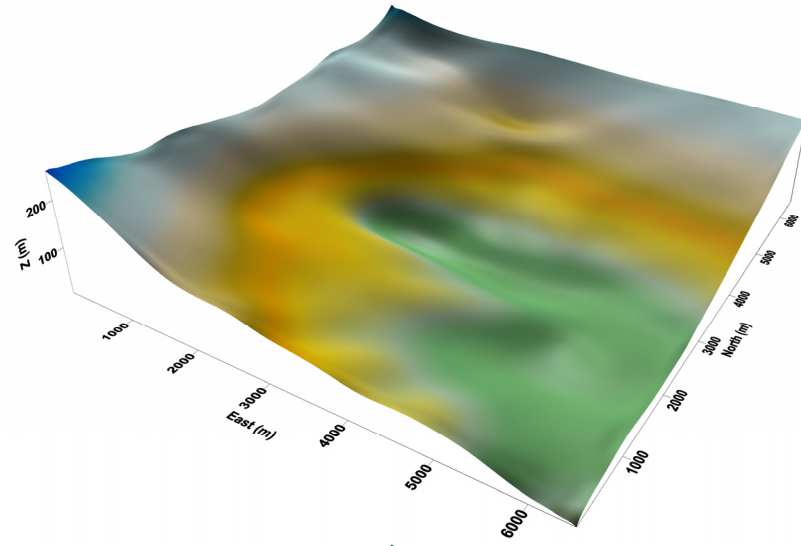
(b)
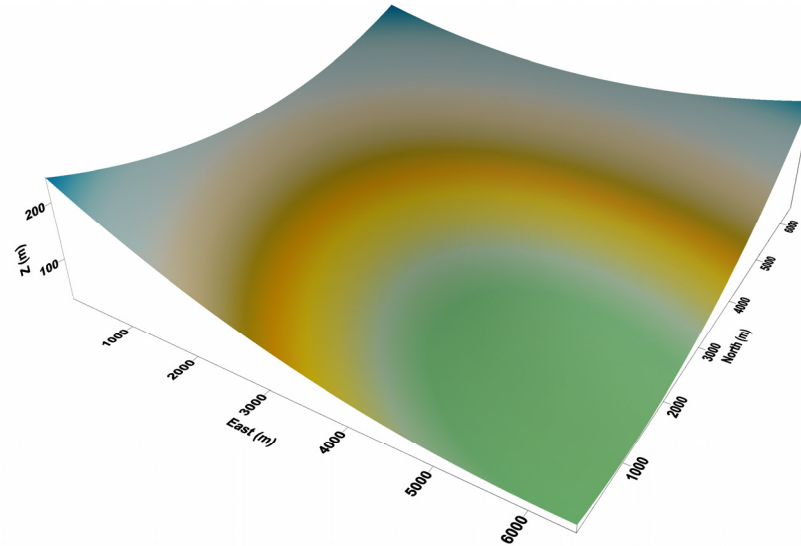
(c)
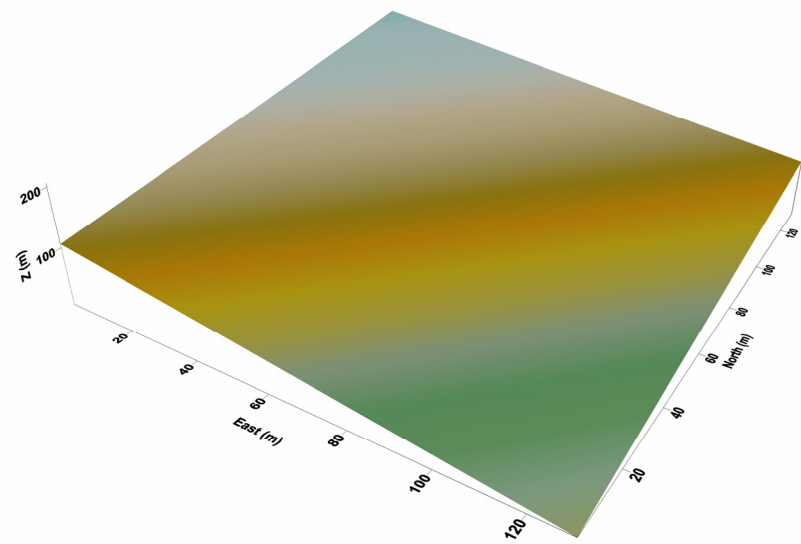
Figure 3-7: An example base surface and transformed base surfaces. (a) original base surface, (b) paraboloid base surface, and (c) incline base surface.

25
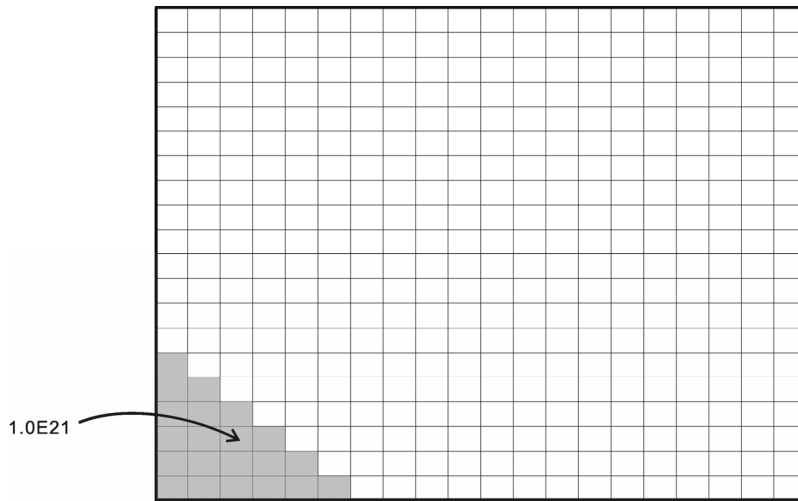
Figure 3-8: Schematic diagram illustrating the mark surface definition. All un-wanted grid cells are signed extremely large values as the indicator of "bad" grids which will not be used for idealized base surface simulation.

When the base surface is transformed, the residuals of the original base surface and the idealized base surface are saved and may be added back after simulation; hence the fluctuation of base surface will be retained in the final surface model. An example base surface and the transformed paraboloid and incline are shown in Figure 3-7. The base surface transform should not be performed if there is resolvable local information in the paleobathymetry. For example, if there are ponded minibasins, the base surface transform could remove this information.

Some part of base surface may be highly deformed which has great influence on the simulated surface shape. To mitigate the influence, a marker surface may be used to constrain the area used for surface fitting. The unwanted grid nodes are not considered (Figure 3-8). At present, only non-faulted structures are considered.

3.2.3 Surface Positioning

Under the assumption that no erosion happens during surface modeling, base surface is unchanged during simulation. However, the top surface is always treated as a global unconformity; any surface above the top surface will be truncated.

The surface positioning algorithm should: (1) respect geologic information with respect to the interrelationship of the architectural elements described by the surfaces, (2) avoid boundary and vertical surface stacking artifacts, (3) result in a reasonable probability of the candidate surface being accepted and (4) be computationally efficient (Pyrcz, 2004).

Surface placement includes the determination of attitude and location. For convenience, we will discuss the two aspects in two sections.

1. Vertical Surface Positioning Rule

According to sequence stratigraphic principles, a candidate surface should ideally be positioned on a base level. Base level is generally regarded as a global reference surface to which long-term continental denudation and marine aggradation tend to proceed (Catuneanu, 2006). The base level is not a real physical surface; it is dynamic, moving upward and downward through time.

(1) Two types of base levels

Global base level is the interactive result of regional basin tectonics, sea-level fluctuations and rate, type and source of sediment supply. Many continental slope base level models and river base level models have been proposed, such as Friedrichs and Wright (2004) and Cronin and Hartley (2000). Usually, the research area for fine-scale deepwater turbidite modeling is only in reservoir scale; therefore, it is impossible to infer and integrate these models into `LE_model` program. As an alternative, a surface fitting methodology is applied to approximate the shape of global base level.

In this thesis, the local base level concept is inferred for fine-scale lobe positioning, but it is much smaller than the conventional local level used in sequence stratigraphy. These base levels are formed by the bathymetric healing process of turbidity current, and not related to any large-scale controlling parameters, such as sea-level change. As a gravity-driven flow, the head does not grow unchecked as suspension from the body of the current overtakes it. Instead, an equilibrium is developed. The rate of body flow into the head region is balanced by loss of suspension from a region of intense turbulence and flow separation at the back of the head. This ejected material settles back into the flow top according to fall velocity, with the coarsest grains returning far behind the head. The result is lateral grading in the flow from a coarser suspension near the head to a finer suspension near the tail. The finer sizes are recirculated at a faster rate, and therefore achieve a greater degree of lateral size sorting (Pickering, 1989). No exchange between turbidity current and former deposition was assumed. In practice, turbidity current releases loads from both head and tail, and absorbs new load into head by eroding former deposition as compensation. The balance is dynamic and results in the evolution of local base level (Figure 3-9). When loss is greater than compensation, a new lobe starts forming. An interesting phenomenon is that each turbidity current smoothes local bathymetry, but new lobes are positioned on a local base level made by former turbidity currents, not by itself.

From above discussion, a local base level is formed by depositional process only. Long-term controlling parameters, such as sea-level change, tectonic movements and depositional supply, control the trend of local base level evolution. Local base level evolution is the driver for global base level formation. There is some literature on the relationship of conventional local base level

and global equilibrium profile of the river-marine system, such as Press and Siever (1986) and Catuneanu (2006). In these publications, local profiles are graded fluvial profiles. Under the assumption that erosion is more significant than accommodation, they always move downward to global base level. In `LE_model` program, we assume that erosion is not so significant; therefore, accommodation is the major component. Under this assumption, local base levels should be always located above base surface and moves upward toward the top surface, which represents the final status of global base level.
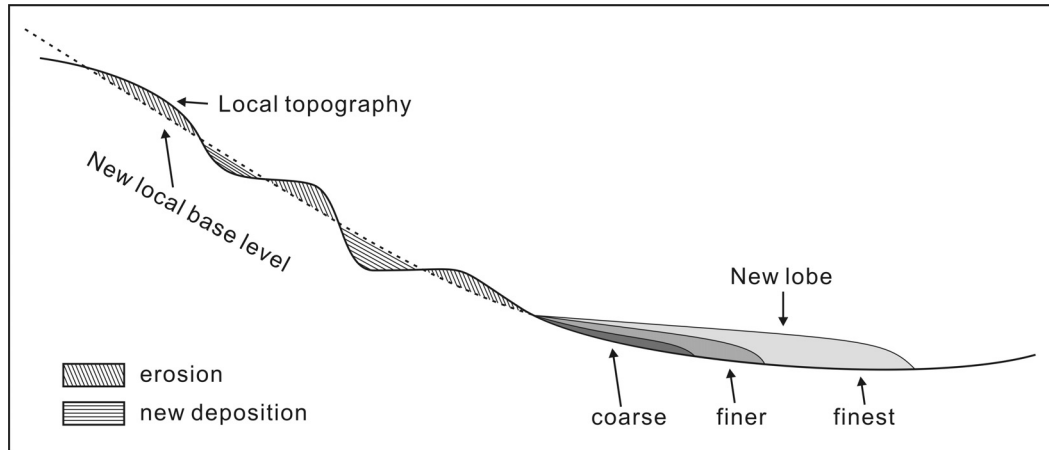
Figure 3-9: A schematic diagram showing the local base profile forming procedure. The vertical scale has been exaggerated to illustrate the local erosion and new deposition process.

(2) Simulation of base levels

For simplification, the same surface fitting methods are applied for both global and local base levels simulation. Base levels have idealized paraboloid or incline shape. After stacking on a base level, a candidate surface does not locally change inclination. There are many algorithms available for paraboloid or incline surface fitting, such as Yu (2001).

For global base level fitting, a mask surface may be applied to screen some highly deformed area since it may have great influence on global base level inference. The idealized shape should be specified by visualizing the shape of the present-day base surface.

The local base levels are dynamically fitted as functions of former simulated surfaces. The surface shape that best meets proposed surface acceptance criterion is selected and no user interaction is needed. The surface acceptance criteria will be discussed below.

(3) Original Surface Placement Rules

The original `LE_model` program positioned a candidate surface on a datum with the global minimum elevation of former surface. Datum updating rate is much slower than surface stacking rate due to (1) the influence of permissible angle, and (2) no constraints on lobe entry point selec-

tion. Therefore, datum is much lower than simulated surface during later stages in the simulation (Figure 3-10).
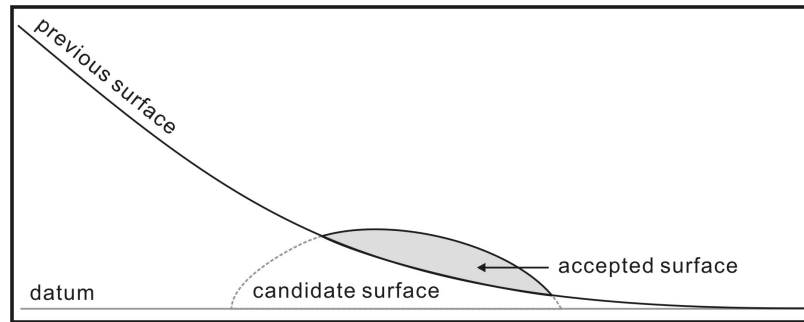
Figure 3-10: Schematic plot showing volume missing problem.

For demonstration, a pair of synthetic bounding surfaces were constructed. The gradient of the base surface is about 2 degrees towards southeast. The bounding surfaces pinch out towards the western and northern edge to mimic the common stratigraphic situation in continental slope environment.

Method I: without transforming base surface

Without base surface transform, 1000 surfaces were generated with final filling proportion of 89.8%. One long section and one cross section are shown in Figure 3-11. In general, the surface model is visually acceptable along longitudinal direction, but it is not realistic in the transverse direction because of the influence of local bathymetry. It does not reproduce a compensational stacking pattern very well. From the cross plot of filling proportion versus number of surfaces, we can see that the filling proportion is in direct proportion to the number of surfaces at initial stage, but more surfaces are needed at a later stage (refer back to the left of Figure 1-4).

Method II: flattening base surface

After flattening base surface, 1000 surfaces were generated to fill 94.99% of the volume. The surface model is visually acceptable in both directions. Figure 3-12 shows the same long-section and cross-section as in Figure 3-11. The missing volume problem at the later simulation stages still exists (refer back to the right plot in Figure 1-4).

(4) New vertical Surface Placement Rules

The new vertical surface positioning rule amounts to recalculate base level for each surface. The workflow of the rule is: (1) a candidate surface is drawn, (2) the base level of this candidate surface is fitted based on local topography, (3) the candidate surface is added on the base level based on its thickness, and (4) the volume below former surfaces is truncated under the assumption that no erosion happens (Figure 3-13).

Long Section 10
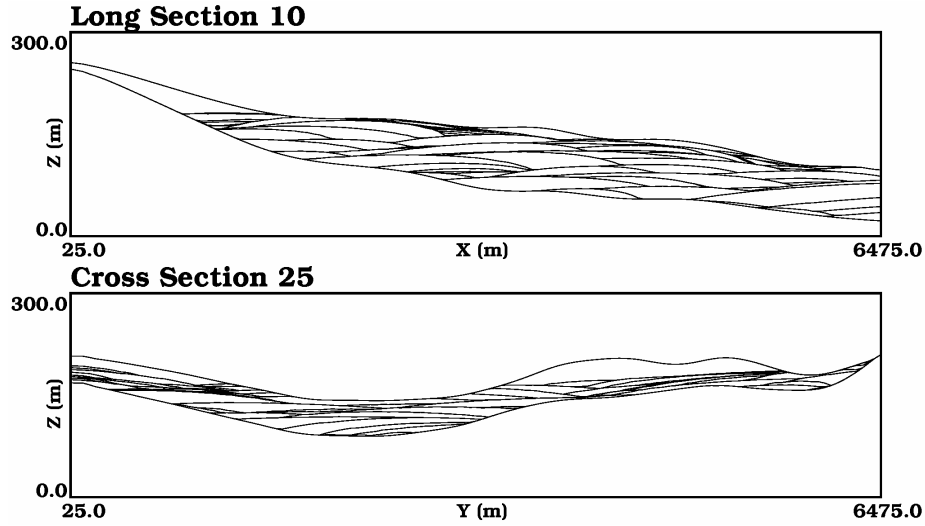
Cross Section 25

Figure 3-11: A long section and a cross section to illustrate the surface modeling results of original surface placement rules without base surface transformation.

Long Section 10
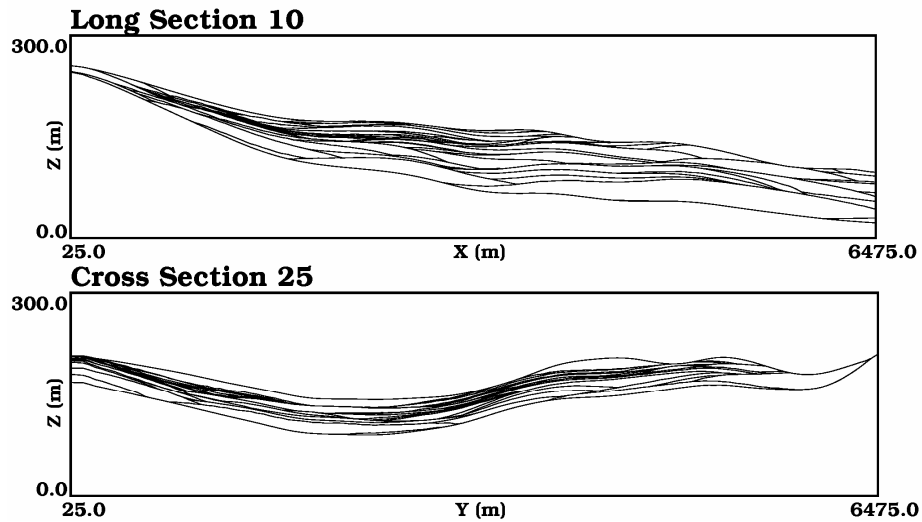
Cross Section 25

Figure 3-12: A long section and a cross section to illustrate the surface modeling results of original surface placement rules with flattening base surface.

For comparison, the same bounding surfaces and surface simulation parameters used in former case study are applied to demonstrate the new surface position rule. Simulation results are shown in Figure 3-14 through Figure 3-17. Spatial structures are geologically realistic. The cross plots of number of surfaces versus filling proportion are shown in Figure 3-18. They all have linear shapes, which means the missing volume problem is essentially solved. Some related statistics are shown in Table 3-2. The target filling proportion is set to 95%. Incline transform is the best in this case study in the sense that fewer surfaces are needed.

2. Areal Surface Positioning Rule

The areal surface positioning rule amounts to the selection of an entry location. As a gravity-driven flow, local bathymetry has great influence on lobe orientation, geometry and positioning. Therefore, the entry location may be a function of previous surface. The entry position may also be independent of previous surfaces. The entry location is chosen independent of previous surfaces method in `LE_model` program. Since the entry location is selected independently, some additional rules are needed as constraints for a reasonable surface position. A reasonable surface model should honour compensational stacking pattern, which is the tendency of flow event deposit to fill topographic lows and to smooth topographic relief.
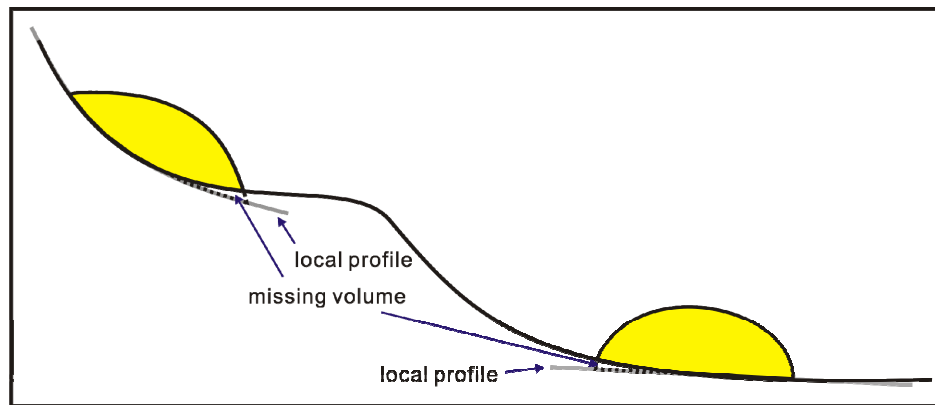
Figure 3-13: Schematic plot showing the vertical surface placement rule.
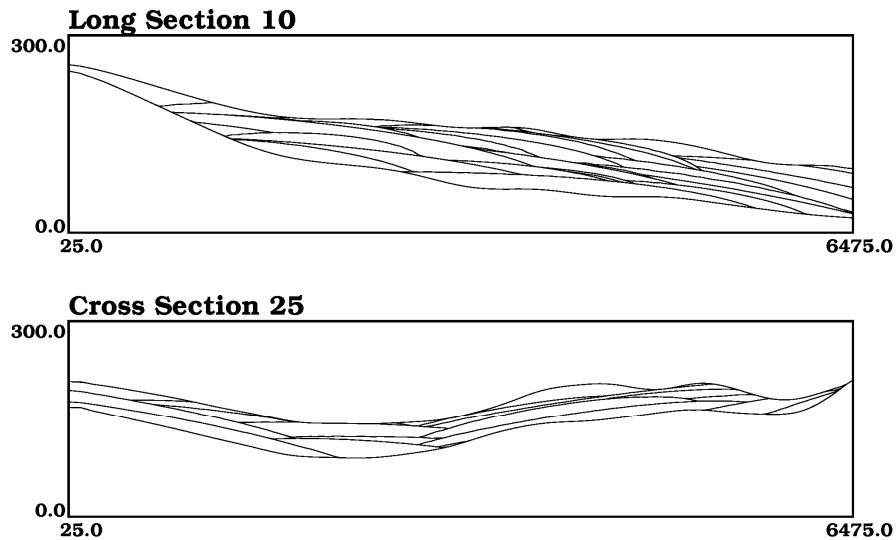
Figure 3-14: Long section 10 and cross section 25. No base surface transform is performed.

Long Section 10

300.0

0.0

25.0   6475.0

Cross Section 25

300.0

0.0

25.0   6475.0
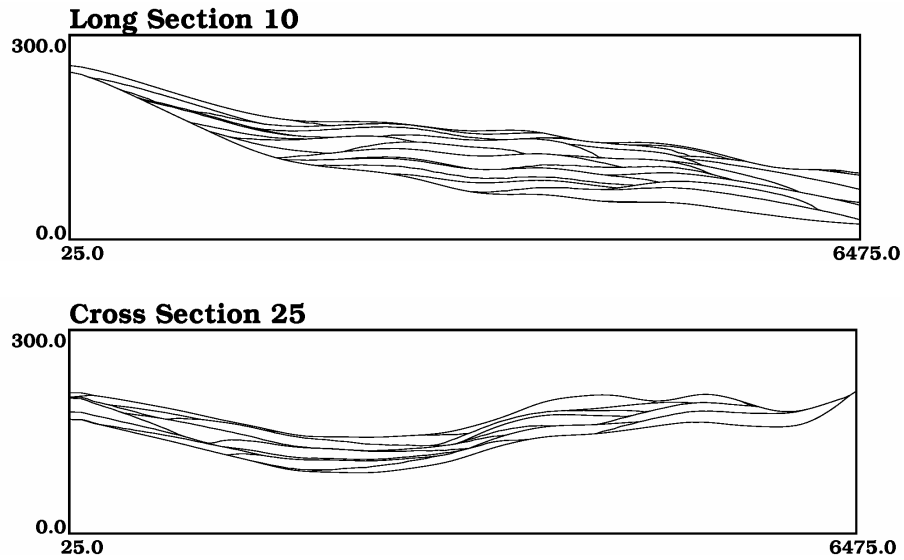
Figure 3-15: Long section 10 and cross section 25. Base surface is flattened during simulation and then back transformed to original shape.

Long Section 10

300.0

0.0

25.0   6475.0

Cross Section 25

300.0

0.0

25.0   6475.0
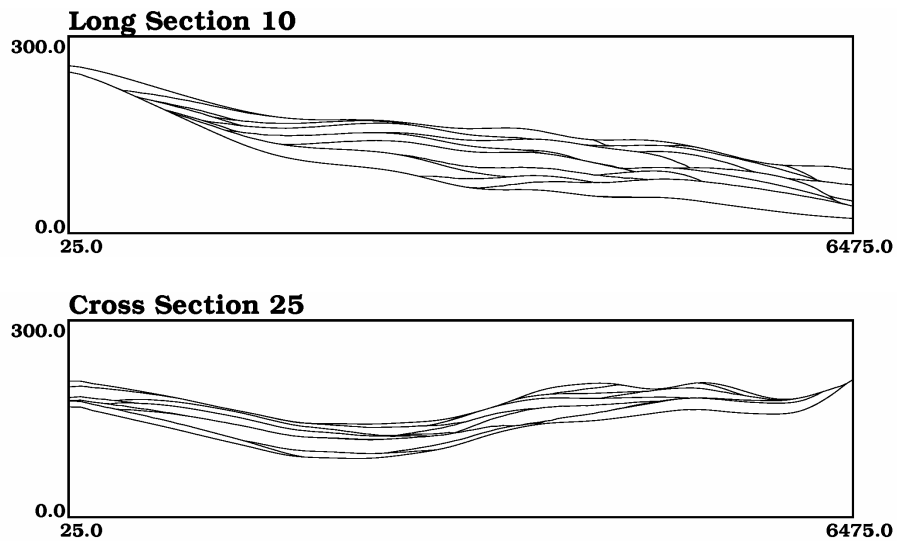
Figure 3-16: Long section 10 and cross section 25. Base surface is transformed to a paraboloid during simulation and then back transformed.

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Long Section 10
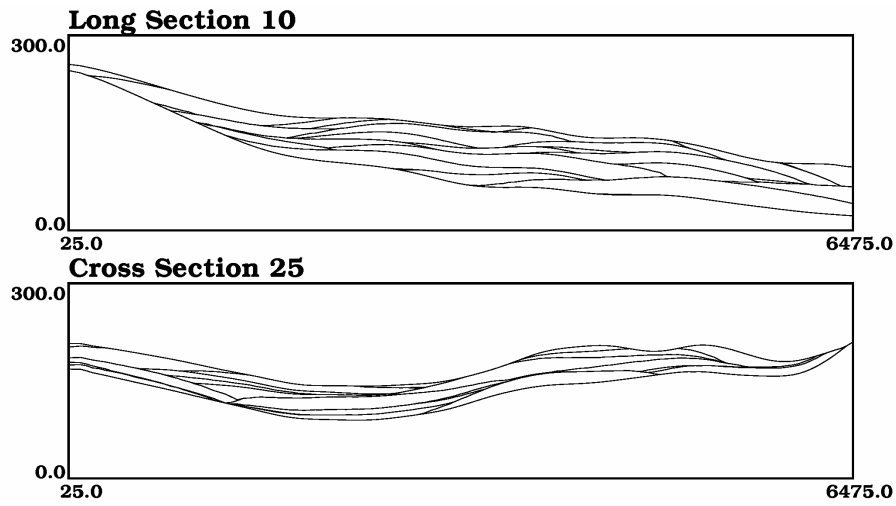
Cross Section 25

Figure 3-17: Long section 10 and cross section 25. Base surface is transformed to an incline during simulation and then back transformed.

(a)

(b)

(c)

(d)
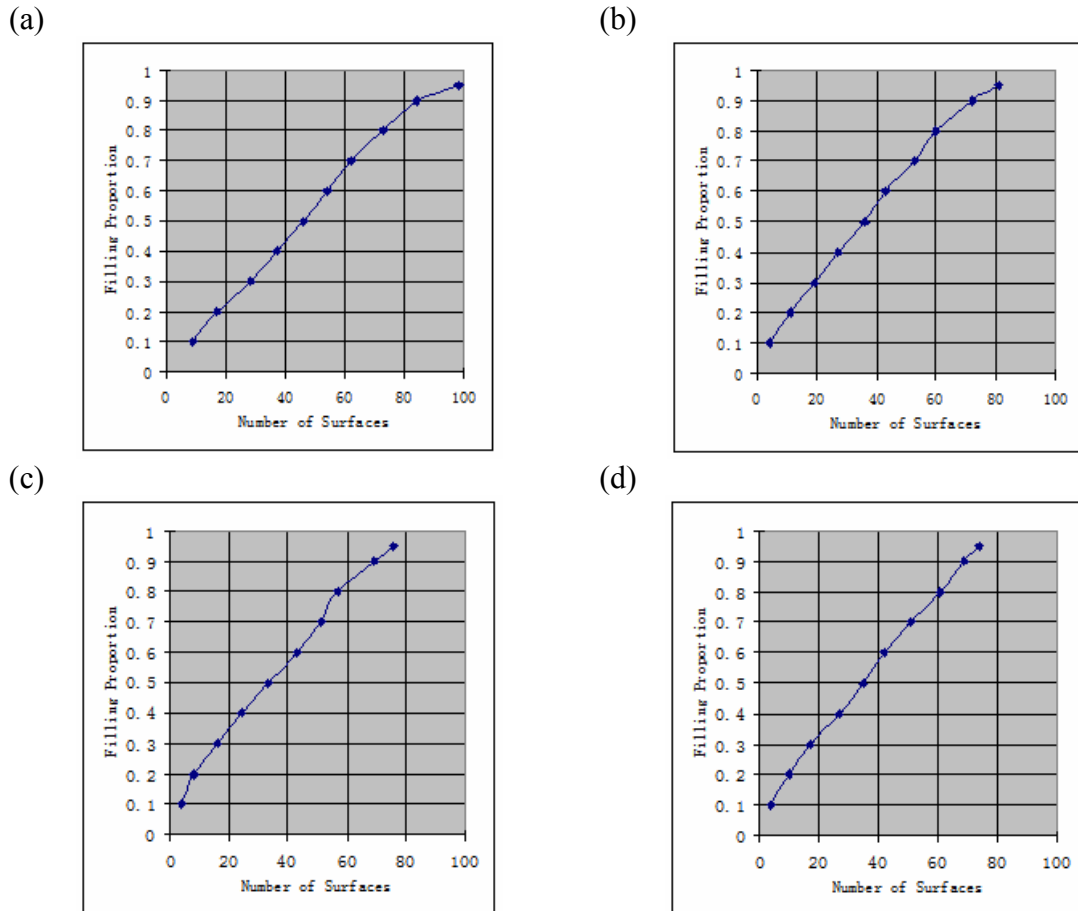
Figure 3-18: The number of surfaces and filling proportion. (a) no base surface transform; (b) flatten base surface; (c) transform base surface to a paraboloid; and (d) transform base surface to an incline.

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Method	Number of surfaces	Filling Proportion
No base surface transform	99	95.3%
Flatten base surface	82	95.3%
Transform base surface to a paraboloid	78	95.1%
Transform base surface to an incline	75	95.3%

Table 3-2: Some statistics of a synthetic case study with different base surface transform approach.

The areal position is selected by the following procedures: (1) an areal surface occurrence probability field is constructed first. The probability is a function of previous surfaces, relative vertical position and remaining volume. A position which is close to a channel entry point, with larger remaining thickness or minimum simulated thickness, and more proximal will have larger occurrence probability; (2) a uniform random number [0.0, 1.0] is drawn; and (3) the position with corresponding cumulative probability is selected as the entry location of a new lobe.

3.2.5 Well Conditioning

An existing well conditioning method for surface-based modeling is the rejection algorithm proposed by Pyrcz (2004). The key steps of the algorithm are: (1) a candidate surface is built, (2) the residual of each available well data to the candidate surface is calculated, (3) if the sum of the residual is less than a specified tolerance, the surface is accepted; or, it is rejected and the procedure is repeated, and (4) the residual is simulated for all locations and added to the surface to ensure exactitude.

The initial tolerance of rejection algorithm is usually set to a small value for smooth surface models. The tolerance may be increased gradually to improve speed, but unexpected short-scale variations may be introduced.

As an improvement, a dual-spline error surface fitting algorithm is proposed in `LE_model` program for fast well conditioning. The surface acceptance criteria and optimal surface selection methodology are modified as follows.

   Surface acceptance criteria:
   1. If the candidate surface does not pass through any wells, it is accepted. For example, the surface A in Figure 3-19.
   2. If the candidate surface passes through only one well, it is acceptable if available surface pick is located within the surface. For example, the surface C in Figure 3-19; surface B is rejected.
   3. If the candidate surface passes through more than one well, it is acceptable if all available well picks are located within the surface. For example, the surface D in Figure 3-19.

Surface conditioning methodology:

1. If the candidate surface passes through only one well, (1) residual of available well pick to candidate surface is calculated, and (2) the surface is shifted downward based on the residual (Figure 3-20).

2. If the candidate surface passes through multiple wells, (1) the residual of each surface pick to the candidate surface is calculated, (2) the minimum residual r_{min} and maximum residual r_{max} are calculated, (3) the candidate surface is shifted downward by distance $\left|(r_{max} + r_{min})/2\right|$, which is the optimal position for the sum of residuals should be close to zero, (4) new residuals are calculated, and (5) a dual-spline error surface is interpolated based on new residuals and added back to candidate surface (Figure 3-21).

The optimal surface position is selected by shifting a candidate surface. No boundary artifact arises during the shifting process. This is the major reason that all available surface picks should be located within a candidate surface.

Figure 3-22 illustrates two possible surface models by conditioning to 36 wells in a case study.
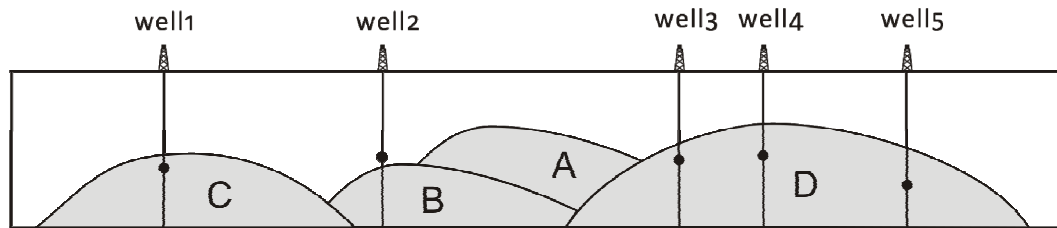
Figure 3-19: A synthetic diagram illustrating the acceptance criteria for well conditioning.
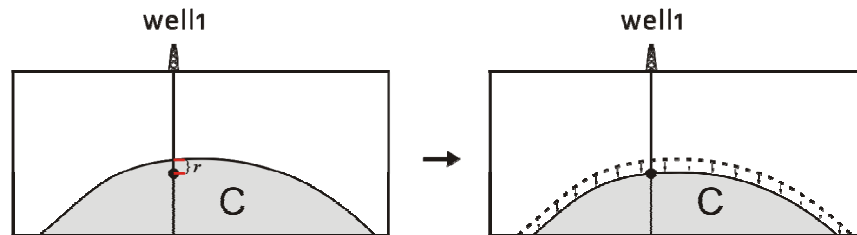
Figure 3-20: Schematic diagram illustrating the well conditioning methodology with one well case. The residual of the available well pick with the candidate surface is calculated first (left plot); then the candidate surface is "lower" down to pass through the available well pick based on the residual (right plot).
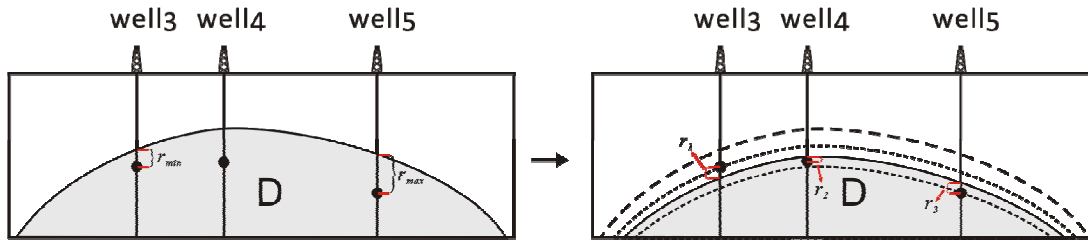
Figure 3-21: Schematic diagram illustrating the well conditioning methodology with multiple wells case. The minimum and maximum residuals are calculated first, i.e., r_{min} and r_{max} on the left plot; then the candidate surface is "lower" down in-between the minimum and maximum residual; after that, the residual of each available well pick to the new surface, r_1, r_2, and r_3, are calculated (the right plot).
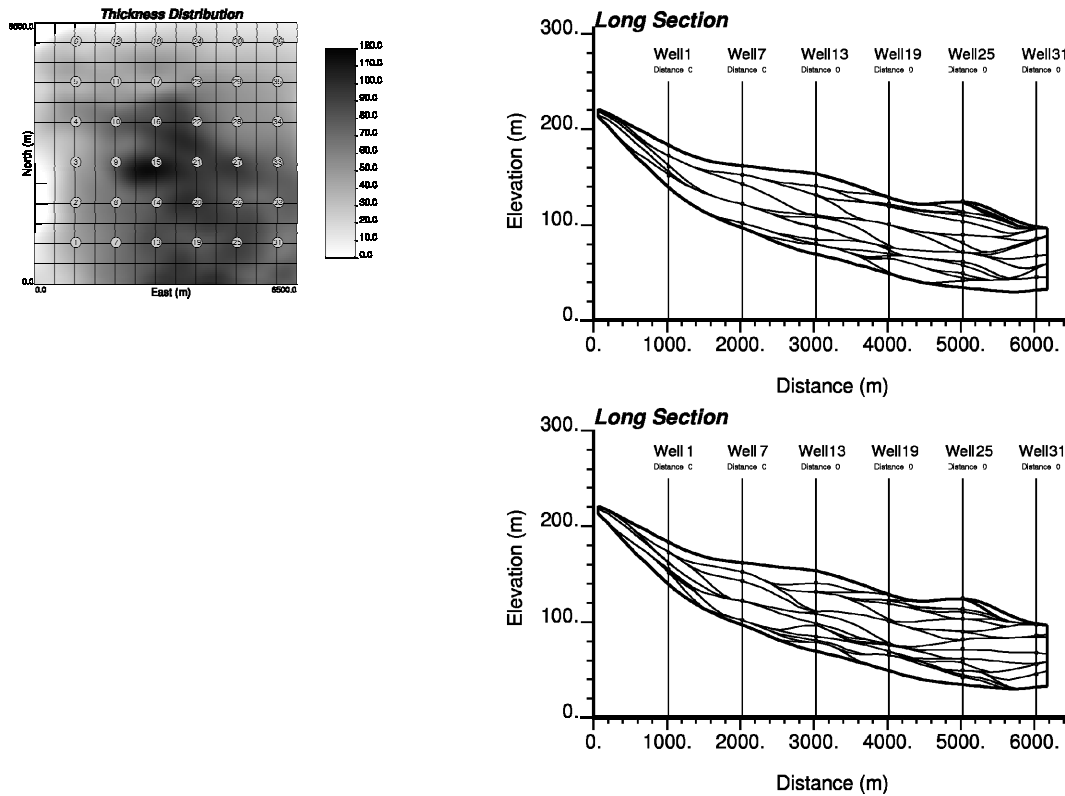
Figure 3-22: The thickness map of the strata and the location map of 36 synthetic wells. Two conditional realizations were built to illustrate possible spatial structures.

3.2.6 Surface Acceptance Criteria

To build geologically realistic surface models, (1) all available surface picks should be honoured, (2) compensational stacking pattern should be honoured, and (3) the input surface geometry statistics should be honoured.

The following surface acceptance criteria should also be met:

Criterion I: *minimum volume ratio* (MVR). MVR is the ratio of lobe volume, V_{lobe}, and gross volume, V_{gross}. To establish a reasonable MVR, the modeler needs to set up all surface modeling parameters and run `LE_model` one time. During surface modeling procedure, (1) V_{gross} is calculated, (2) an ideal lobe with geometry of all means parameters is built, (3) ideal lobe volume, V_{ideal}, is calculated, and (4) the ratio of V_{ideal}/V_{gross} is a good reference to set up the MVR parameter. Ideally, $(0.5-0.8) \cdot V_{ideal}/V_{gross}$ is a good starting point. A larger MVR will lead to larger candidate surfaces, which accelerates the well conditioning process significantly.

Criterion II: *maximum missed volume ratio* (MMVR). MMVR is the ratio of missed lobe volume, V_{missed}, and the ideal lobe volume, V_{ideal}. Therefore, MMVR is also defined in relative scale. Unlike MVR, MMVR is not related to gross volume. MMVR is calculated by, (1) a candidate surface is drawn and its ideal volume, V_{ideal}, is calculated, (2) the candidate surface is positioned on the local base level and the volume below previous surfaces is truncated, (3) the remaining volume, V_{remain}, is then calculated, and (4) MMVR, that is, $(V_{ideal}-V_{remain})/V_{remain}$, is calculated. Ideally, MMVR should be less than 0.2. A smaller MMVR will lead to a smaller candidate surface, so less volume is truncated. However, well conditioning may be a problem for these small surfaces.

Both MVR and MMVR will lead to compensational stacking pattern (Figure 3-23). MMVR is easier to establish, however, MVR criterion is applied in `LE_model` for faster well conditioning. Figure 3-24 compares the simulation results of above two surface criteria. All simulation parameters are the same except for the surface acceptance criterion. Only 23 surfaces are needed for MVR; while 113 are required for MMVR.

3.2.7 Stopping Criteria

Surface modeling will stop when one of the following criteria is met:
1) User-specified volume filling proportion is reached.
2) No available surface pick exists.
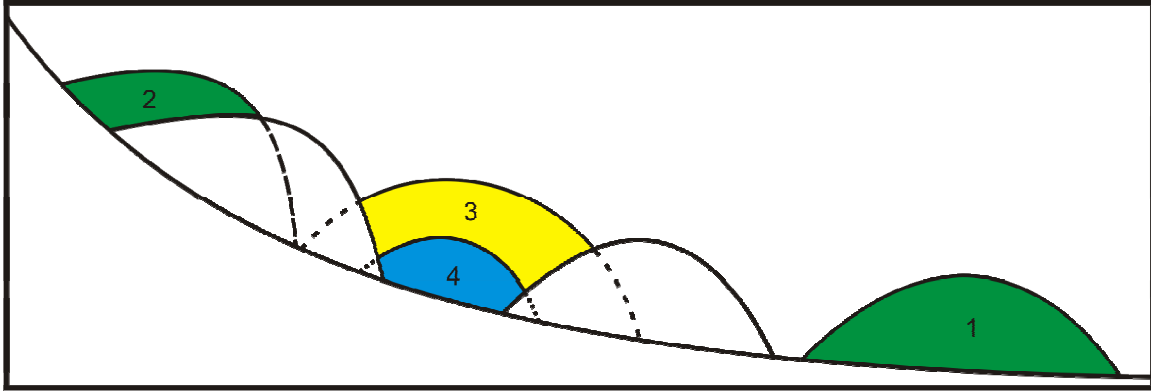
Figure 3-23: Synthetic diagram illustrating acceptable surface under different criterion. Surface 1 is acceptable under both criteria; surface 2 is not acceptable under both criteria; surface 3 is acceptable for MVR only, while surface 4 is acceptable for MMVR only.
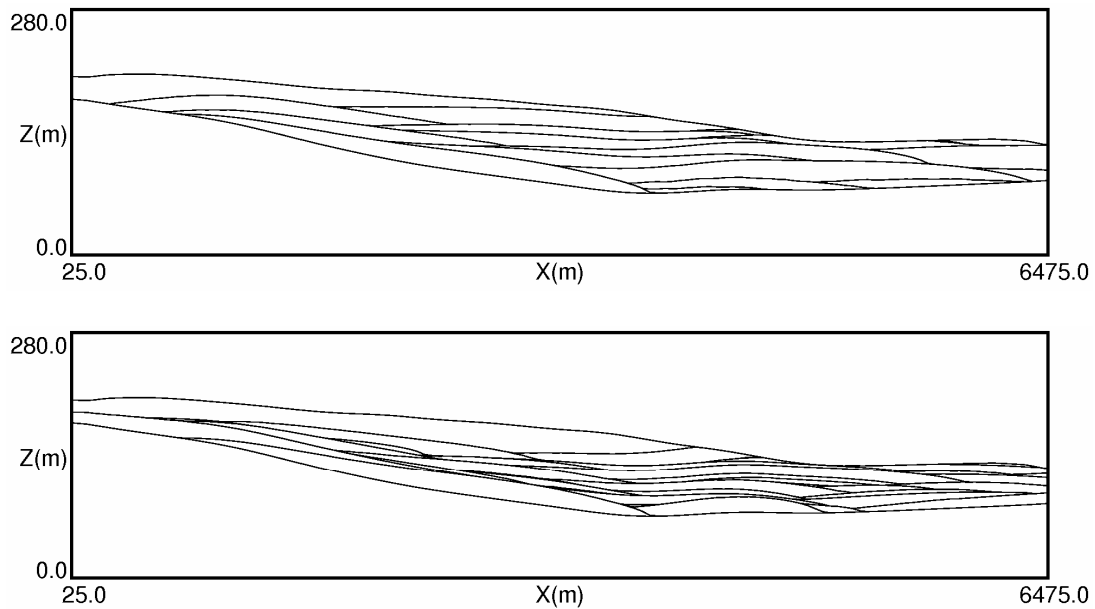
Figure 3-24: Comparison the results of two surface criteria. Above: MVR; Below: MMVR.

3.2.8 Discussion

In this section, prototype research into erosion simulation and the reproduction of stacking patterns will be presented.

1. Erosion Simulation

There are two types of erosion in second-order lobes simulation, depositional erosion and unconformities. As discussed earlier, depositional erosion is the major drive for local base levels. Although we introduced the concept of local base level, no erosion was included in the developed program. Besides depositional erosion, unconformities may also occur. Erosion simulation aims at reproducing more complicated spatial structures.

38

(1) Global unconformities simulation

Global unconformities may be visualized on seismic. They are the result of long time scale controlling parameters, such as tectonic movements. If an unconformity can be continuously traced on seismic, it can be treated as an additional boundary surface dividing the reservoir into different units for modeling. The following approach may be applied:

a) Both bounding surfaces are transformed to idealized shape, i.e. paraboloid or incline, to represent the global base levels at those time stages.

b) We assume that unconformity is located between the global base levels in proportion to time/thickness (Figure 3-25).

c) When wells are available, the unconformity may be locally adjusted to honour wells.

d) All surfaces above the unconformity are truncated until the volume below the unconformity is 100% filled.

e) Back transform base surface to its original shape to introduce local fluctuations back.

Figure 3-26 illustrates the global unconformity simulation effect based on above methodology.

(2) Depositional erosion simulation

As discussed earlier, local base level results from the balance between the head and body within turbidity current, and the balance between turbidity current and former deposition. To simulate erosion events, former deposition above base level should be truncated. The accommodation, that is, the space between local base level and former deposition, is refilled (Figure 3-27). We assume that the erosion ability decreases to zero as long as a new lobe is formed; therefore, local base level is adjusted to pass through the entry position. A long section is shown in Figure 3-28 to illustrate the depositional erosion methodology. The corresponding section without erosion simulation is shown in the below of Figure 3-24. 158 surfaces are generated; while it is 113 for no-erosional case.

The program developed in this thesis can only be used without well data for depositional erosion simulation at present.

2. Honouring Stacking Patterns

There are three stacking patterns that can be simulated with the `LE_model`, aggradation, progradation and retrogradation. As we mentioned earlier, the entry position in `LE_model` is selected by randomly picking in areal surface occurrence probability field. The distribution of surface occurrence probability field will have a significant influence on surface entry position selection. Therefore, different surface stacking pattern may form. For example, if proximal positions get higher surface occurrence probabilities, a proximal position will be preferentially picked

as entry location. Some sections are shown in Figure 3-29 to illustrate the reproduction of surface stacking patterns.
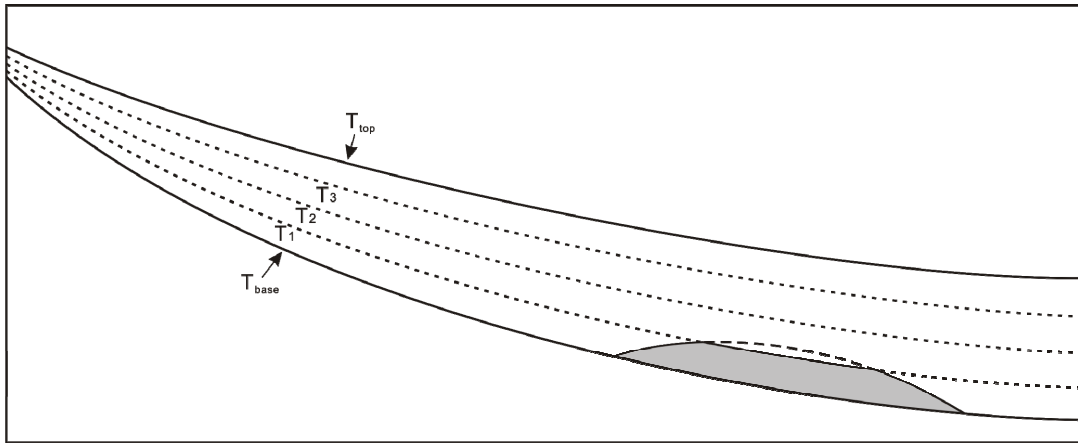
Figure 3-25: Synthetic diagram illustrating the global unconformities modeling methodology. Interim time surfaces T_1, T_2 and T_3 are constructed by their relative positions between T_{base} and T_{top}. A candidate surface above T_1 is truncated to illustrate the erosion effect.
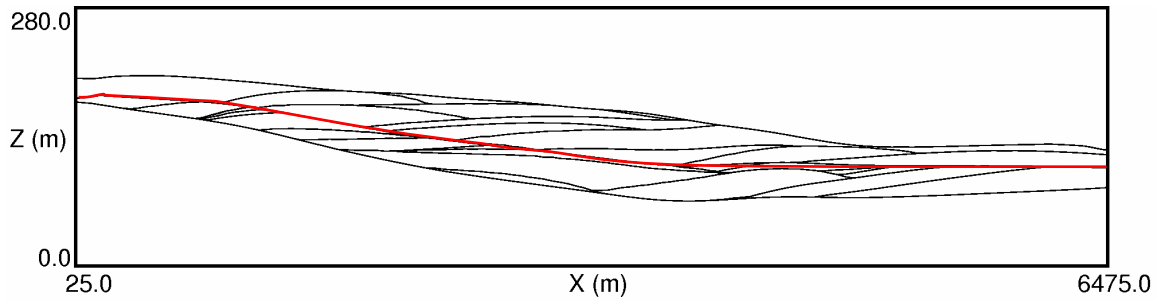
Figure 3-26: A long section to illustrate the global unconformity simulation. Only one global unconformity exists in this synthetic case study.
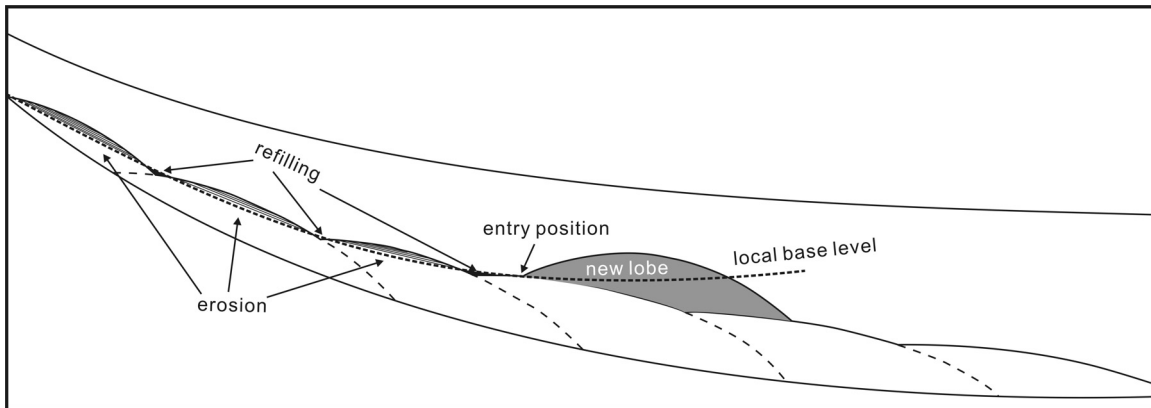
Figure 3-27: Schematic plot showing the erosion rule. Both base and top surfaces have been transformed to paraboloid. The current candidate surface is highlighted with light gray color. The equilibrium is shown with dash line. The local geometry used for equilibrium fitting is illustrated as the heavy gray solid line.
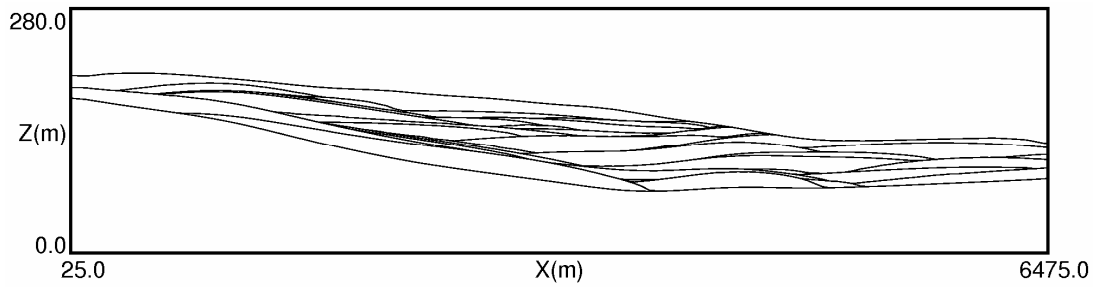
Figure 3-28: A long section to illustrate the depositional erosion simulation result.
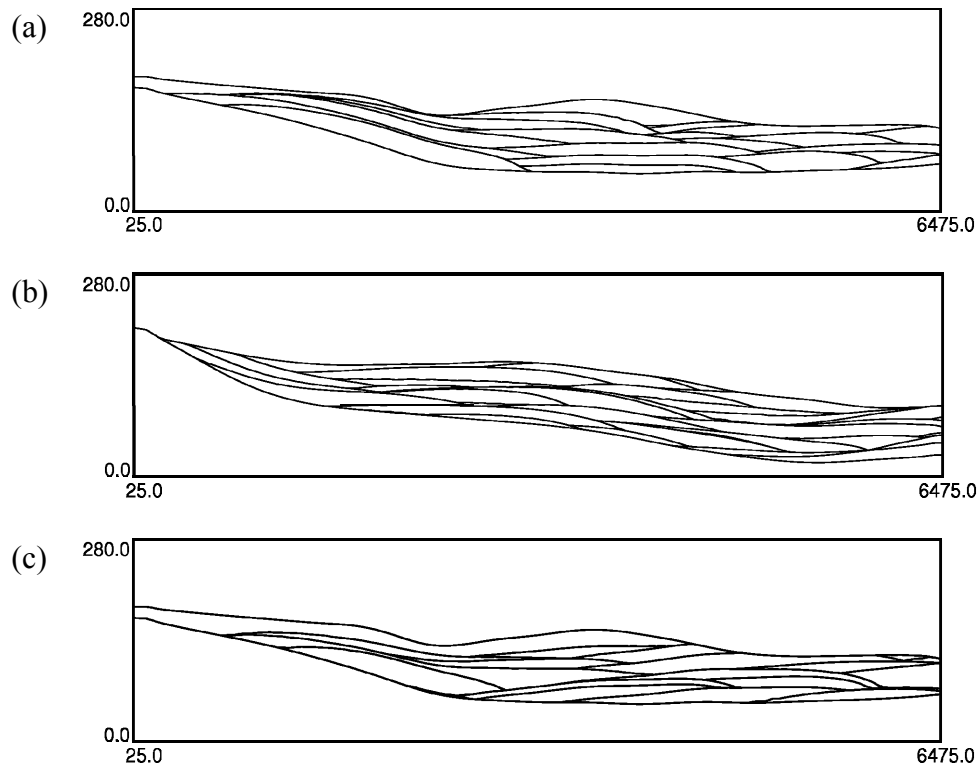
Figure 3-29: The stacking patterns: (a) aggradation, (b) progradation, and (c) retrogradation.

3.2.9 Parameters for `LE_model`

The parameter file for `LE_model` includes specification of well data, boundary surfaces, grid definition, lobe geometry and trend definition and facies trend template. An example parameter file is shown below and an explanation for each parameter is provided in Table 3-3.

```
Parameters for LE_model:

1. well.dat        - well file
2. 1 2 3 4 5 6 7 8 - data columns
3. bot.out         - file with base surface
4. 1               - column for variable
5. top.out         - file with top surface
6. 1               - column for variable
7. 1 bound.dat     - using boundary (0=no,1=yes),boundary file
8. 3               - flatten method (0=no,1=base,2=paraboloid,3=incline)
9. 0               - honour erosion (0=no,1=yes)
10. 130 25. 50.    - nx,xmn,xsiz
11. 130 25. 50.    - ny,ymn,ysiz
12. 280 .5 1.      - nz,zmn,zsiz
13. 2              - number of entry locations at Xmin
14. 40 80          - Y locations of entry locations
15. 70             - angle of permissible deposition
16. 0.030          - minimum lobe volume
17. 0.95           - fraction of the model to fill
18. 1              - honour thickness trend? (0=no,1=yes)
19. 2              - number of trend control points
20. 0.0  15. 3.    - depth(1),thickness(1),standard deviation(1)
21. 300. 35. 3.    - depth(2),thickness(2),standard deviation(2)
22. 2500 0.3       - L:  length  - mean and CV
23. 2000 0.3       - W:  width     - mean and CV
24. 25.0 0.3       - T:  thickness - mean and CV
25. 0.10 0.3       - w/W: width of entry/width - mean and CV
26. 1              - stacking pattern (1=aggradation,2=retrogradation,3=progradation)
27. 76067          - random number seed
28. 1 4            - facies proportion, number of facies
29. .0 .7 .4 .0    - xx1(1),zz1(1),xx2(1),zz2(1)
30. .0 1. .6 .0    - xx1(2),zz1(2),xx2(2),zz2(2)
31. .2 1. .8 .0    - xx1(3),zz1(3),xx2(3),zz2(3)
32. 1              - output format(1=BlockSIS,2=sisim_lm)
33. LE_model.out   - output surface file
34. Localmean.out  - output local mean file
35. 3              - debugging level
36. LE_model.dbg   - debugging file
```

Line	Description
1	Input file with well data. The file should be in GeoEAS format.
2	Column numbers for the well, x, y, z locations and marker code. The x2, y2, z2 are used for no information intervals. The codes are 1 – gradational, and 2 – no information.
3-4	Input file with base surface data, and its column number. The file should be in GeoEAS format.
5-6	Input file with top surface data, and its column number. The file should be in GeoEAS format.
7	Indicator for using boundary file *ibnd*: 0 – no, 1 – yes. If *ibnd* = 1, a boundary file should be specified. The file should be in GeoEAS format, and the data out of interest area will be given extreme large values.
8	Base surface flattening method, 0 – no flattening, 1 – flatten to horizontal, 2 – transform to paraboloid and 3 – transform to incline.
9	Indicator for honouring global unconformity, 0 – no, 1 – yes.
10-12	The regular grid parameters.
13	The number of entry locations at xmin.
14	The Y locations of entry locations.
15	The angle of permissible deposition.
16	The minimum lobe volume. It is in relative scale, and it equals to real lobe volume / gross volume.
17	The fraction of the model to fill.
18	Indicator for honouring lobe thickness trend *ithk*, 0 – no, 1 – yes.
19-21	The lobe thickness trend definition if *ithk* = 1. The trend is defined in real scale and a linear trend template is applied. User needs to specify the number of trend control points, the depth, the mean and standard deviation of lobe thickness at each control point.
22-25	Lobe geometry definition, including lobe length, width, thickness and width ratio w/W.
26	Stacking pattern, 1 – aggradation, 2 – retrogradation, 3 – progradation
27	Random seed
28	Indicator for facies proportion calculation, 0 – no, 1 – yes. Number of facies and facies template type, 0 – 1D vertical trend, 1 – 2D trends. See Chapter 4 for detail.
29-31	Facies trend template definition.
32	Facies proportion output format, 1 – BlockSIS, 2 – sisim_lm.
33	File with output surface.
34	File with output facies proportions.
35	Debugging level.
36	File with debugging information.

Table 3-3: A description of the `LE_model` parameter file.

3.3 Advances in strataform modeling

`Surfsim` program was designed by Pyrcz (2004) to build stochastic surface-based realizations that honour surface geometry and erosional and gradational well contacts for strataform deposits. Original `Surfsim` program assumes:

1) Near parallel bedding; therefore, the surface template is a plane. One possible application of `Surfsim` is to model sheet architectural elements in distal fine grained turbidites.

2) The vertical location is chosen such that an average thickness (drawn from a lognormal distribution with a user defined average and standard deviation) is honoured. Thickness trend modeling is not available.

3) The bounding surfaces are assumed to be non-angular unconformities. A candidate surface will be truncated by bounding surfaces if it tends to extend beyond a boundary.

The improvements developed in this thesis aim at making `Surfsim` more flexible and powerful, so that it can be applied to more complicated geological settings, such as deformed strata.

3.3.1 Boundary surfaces transform

The bounding surfaces are often planar in distal fine-grained deepwater turbidites. Geological deformation and faulting are very common in continental slope environments. A common solution is to transform the bounding surfaces to their original shape for simulation, then transform them back to current shapes after simulation.

1. Methodology

Two boundary surfaces transform approaches are applied:

1) flatten base surface to a horizontal plane,

$$z_{rel_i} = z_i - z_{cb_i}, \forall i \in A_2 \tag{3.13}$$

where z_{cb} is the correlation base, z is the current elevation, z_{rel} is the relative stratigraphic coordinate. The coordinate z_{rel} is 0 at the stratigraphic base and thickness of the bounding surfaces at the stratigraphic top.

This transform may be reversed by:

$$z_i = z_{rel_i} + z_{cb_i}, \forall i \in A_2 \tag{3.14}$$

2) transform bounding surfaces proportionally,

$$z_{rel_i} = \frac{z_i - z_{cb_i}}{z_{ct_i} - z_{cb_i}} \cdot T, \forall i \in A_2 \tag{3.15}$$

where z_{ct} is the correlation top, T is the average thickness of the bounding surfaces. The coordinate z_{rel} is 0 at the stratigraphic base and T at the stratigraphic top.

This transform may be reversed by:

$$z_i = z_{cb_i} + \frac{z_{rel_i}}{T} \cdot (z_{ct_i} - z_{cb_i}), \forall i \in A_2 \tag{3.16}$$

2. Demonstration

Figure 3-30 shows example boundary surfaces in continental slope environment.

1) Without boundary surfaces transform, `Surfsim` does not work well (plot (a) in Figure 3-30). This is due to the intrinsic assumptions of `Surfsim`.

2) After flattening base surface to a horizontal plane, `Surfsim` works very well (plot b in Figure 3-30). The top surface intersects with the base surface in this case, so the simulated surfaces have onlap stratigraphic correlation style.

3) When transforming the bounding surfaces proportionally, new base and top surfaces are parallel with each other. The vertical position of a surface is in proportion to the thickness of the bounding surfaces; therefore the simulated surfaces follow the stratigraphic shape and pinch out towards west.
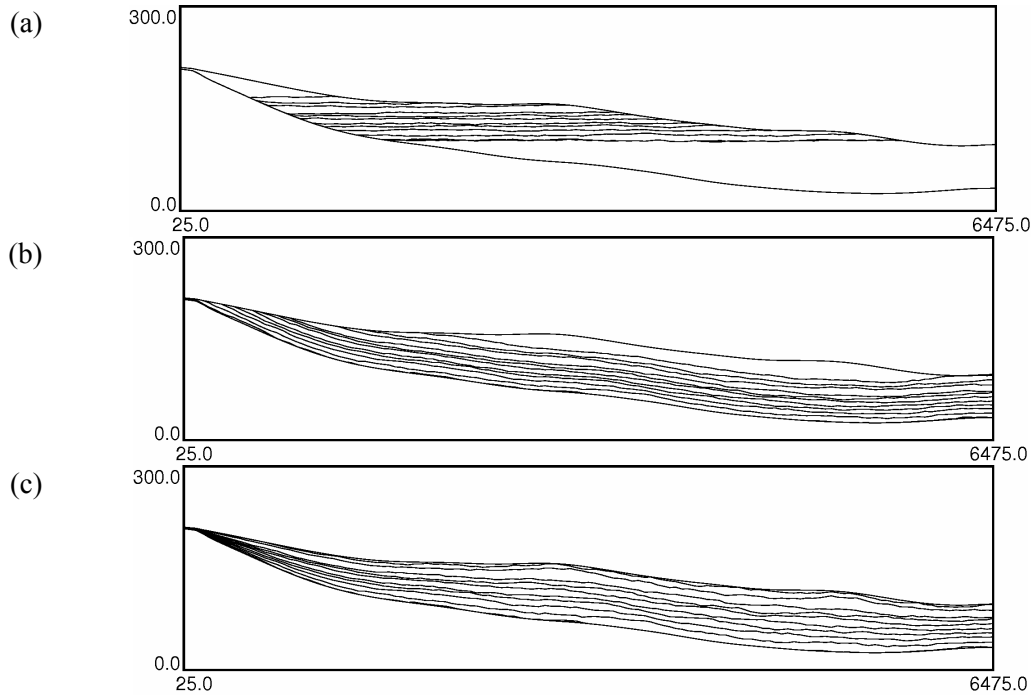
Figure 3-30: Long section 25 to illustrate the surface modeling effect with different boundary surfaces transform algorithms: (a) no transform, (b) flatten the base surface to a horizontal plane, and (c) transform the bounding surfaces proportionally.

3.3.2 Piecewise linear trend modeling

A piecewise linear trend template for the layer thickness is proposed and can be reproduced in simulation. The program can be easily modified to honour any types of vertical trend. The trend is defined in relative scale and within the range of [0, 1] (Figure 3-31). The minimum elevation of the base surface is set as 0.0, and the maximum elevation is set as 1.0. Instead of drawing the thickness mean from a lognormal distribution, it is chosen from the trend template. Note that the thickness of the current surface is a function of former surfaces, so these surfaces are correlated with each other.
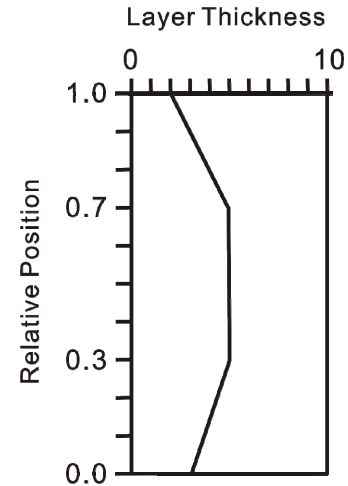
Figure 3-31: Relative thickness trend definition.

1. Demonstration

Figure 3-32 shows two thickness trend reproduction results. The left plot has a standard deviation 0.1; thickness is centered on the trend with small fluctuation. The left plot has a standard deviation 1.0; therefore, the thickness shows great dispersion. In both cases, the thickness trends are well reproduced.

2. Discussion

Figure 3-33 and Figure 3-34 show 2 sections simulated with `Surfsim`, one was conditionally built and another was unconditionally built.

In the conditional realization, the conditioning data control the simulation result. Apparent thinning-upward trend exist due to the distribution of well data. On the unconditional realization, 4 cycles exist. An unrealistic trend may be introduced with limited information; conditioning ensures a realistic trend in thickness.

3.3.3 Honour common stratigraphic correlation style

The assumption of `Surfsim` is that the base surface is always a non-angular unconformity, and the top surface is an unconformity. This is not always true. The common stratigraphic correlation styles, including unconformity, onlap, downlap, stratigraphic pinch out, may all be reproduced by the modifications developed in this thesis.

1. Unconformity and conformity

When top surface is not parallel to base surface, it is assumed to be an unconformity; or it is assumed to be a nonangular unconformity. The conformity contact of top surface can be honoured by setting a smaller filling proportion. Angular unconformity can be honoured by using an

incline surface template, instead of a planar template (Figure 3-35). The dip can be defined by the user.

2. Onlap

When top surface is not parallel to base surface, onlap can be honoured by flattening the base surface to a plane. When top surface is parallel to base surface, onlap can be honoured by using an incline surface template.

3. Downlap

Downlap can be honoured by using an incline surface template only.

4. Stratigraphic pinch-out

It can only be honoured by using proportion bounding surfaces transform when the bounding surfaces pinch out somewhere.
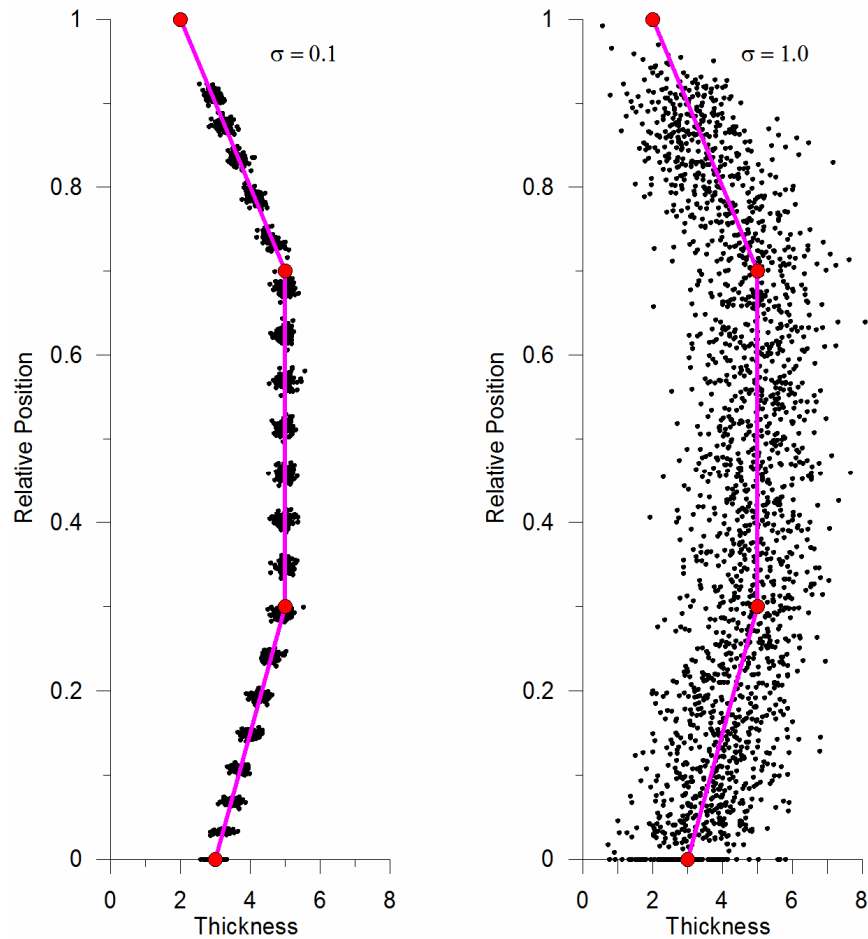
Figure 3-32: Comparing the layer thickness of 99 realizations with the trend definition. The standard deviation for each layer is set to 0.1 on the left plot, and it is set to 1.0 on the right plot.
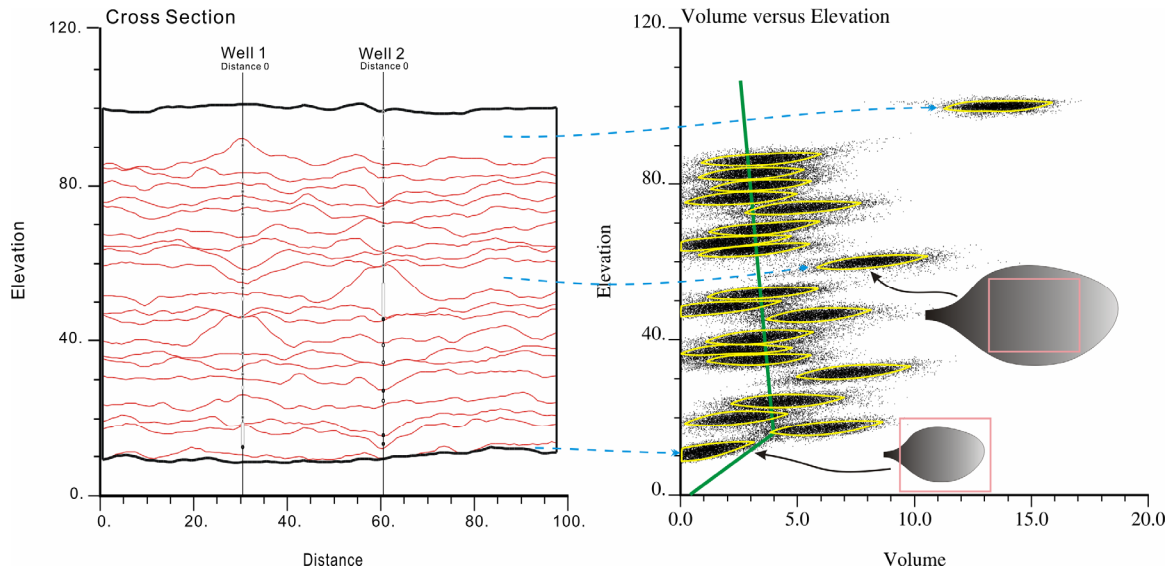
Figure 3-33: The vertical thickness trend of a section of conditional `Surfsim` realization. Thinner upward trend is very clear due to the conditioning data.
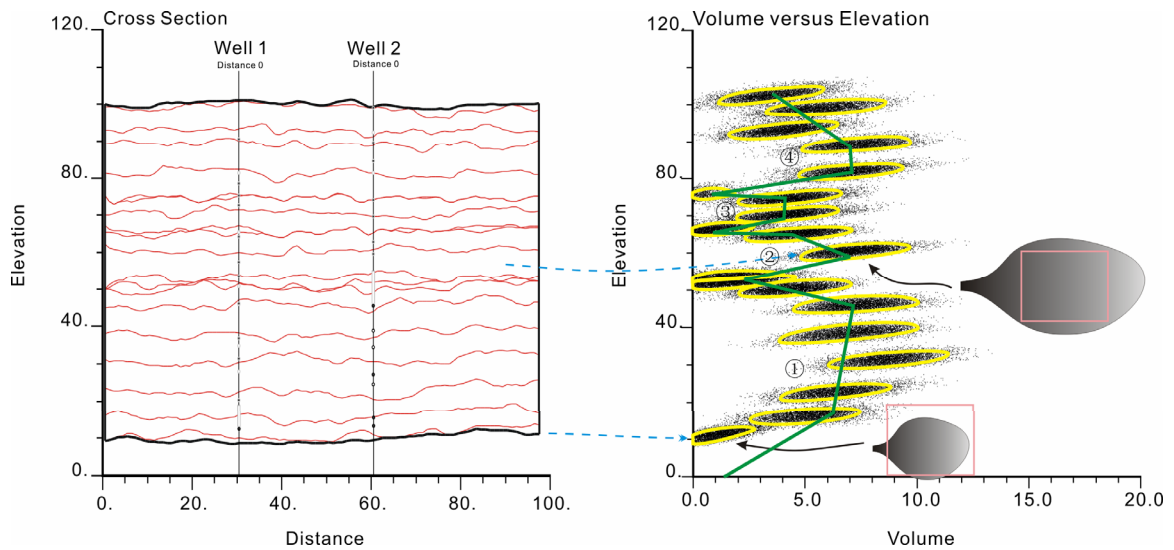
Figure 3-34: The vertical thickness trend of a section of unconditional `Surfsim` realization. It looks that 4 cycles (sequence) exist. The boundaries are the same as those in Figure 3-32 and wells are also plotted to show that this is an unconditional realization.

```
120.0
```



```
0.0
  25.0                                                                    2475.0
```
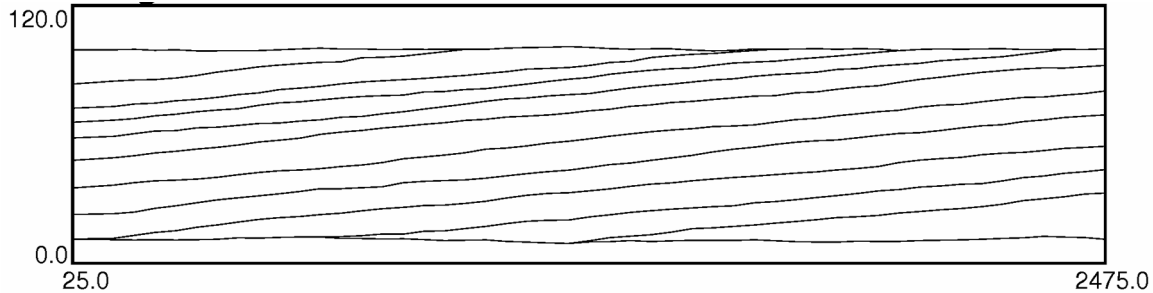
Figure 3-35: An angular unconformity modeling example.

3.3.4 Parameters for `Surfsim`

Some new parameters are introduced into `Surfsim` for these newly developed functions. The
new `Surfsim` parameter file includes well data, boundary surfaces, flattening method, grid defi-
nition, filling proportions, vertical trend definition and simulation parameters (search and
semivariogram) for the 2D simulation of the residual. An example parameter file is included be-
low and an explanation for each parameter is provided in Table 3-4.

```
PARAMETERS for Surfsim:

1. well.dat                - file with data
2. 1 2 3 4 5 6 7 8         - well,x1,y1,z1,x2,y2,z3,code,.
3. 1                       - well conditioning (0=no,1=yes)
4. top.out                 - file with top surface
5. bot.out                 - file with bottom surface
6. 0                       - flatten method (0=no,1=base,2=proportional)
7. 100   0.5  1.0          - nx,xmn,xsiz
8. 50   0.5  1.0           - ny,ymn,ysiz
9. 150   0.5  1.0          - nz,zmn,zsiz
10. 1                      - number of realizations to generate
11. 69069                  - random number seed
12. 0.90                   - fraction of the model to fill
13. 5.0 2.0                - mean and stdev of thickness
14. 1   4                  - vertical trend? (0=no, 1=yes), no. of control points
15. 0.0 3.0 2.0            - 1st: relative depth, thickness, stddev
16. 0.3 5.0 2.0            - 2nd: relative depth, thickness, stddev
17. 0.7 5.0 2.0            - 3rd: relative depth, thickness, stddev
18. 1.0 2.0 2.0            - 4th: relative depth, thickness, stddev
19. 20                     - maximum number of surfaces
20. 1.0                    - gradient of surface in degrees
21. 0                      - output option (0=process,1=all surfaces)
22. surfsim.out            - file for simulation output
23. surfsimgrid.out        - file for simulation grid output
24. surfvol.out            - file for surface volume output
25. 0                      - debugging level: 0,1,2,3
26. surfsim.dbg            - file for debugging output
27. 12                     - number of simulated nodes to use
28. 1      3               - multiple grid search (0=no, 1=yes),num
29. 10.0 10.0              - maximum search radii (hmax,hmin)
30. 0.0                    - angle for search ellipsoid
31. 51  51                 - size of covariance lookup table
32. 1  0.1                 - nst, nugget effect
33. 1  0.9 0.0             - it,cc,ang1
34.        10.0 10.0       - a_hmax, a_hmin
```

Line	Description
1	Input file with well data. The file should be in GeoEAS format.
2	Column numbers for the well, x, y, z locations and marker code. The x2, y2, z2 are used for no information intervals. The codes are 0 – erosional, 1 – gradational, and 2 – no information.
3	Indicator for well conditioning, 0 – no, 1 – yes.
4-5	Input files with boundary surfaces data. Files should be in GeoEAS format.
6	Flatten method, 0 – no, 1 – flatten base surface, 2 – proportional flattening.
7-9	Regular grid definition.
10	Number of realizations to generate.
11	Random seed.
12	Fraction of the model to fill.
13	Mean and standard deviation of thickness.
14	Indicator for honouring vertical trend, 0 – no, 1 – yes. Number of controlling points. Piecewise linear trend template is applied at present.
15-18	The depth, thickness and standard deviation for each controlling point. The depth is in relative scale.
19	Maximum number of surfaces.
20	Gradient of surface in degrees. 0 degree means horizontal surface template.
21	Output option. 0 – output interim surfaces for each stage for surface evolution checking, 0 – output final surface model only.
22	File with surface model.
23	File with simulation grid.
24	File with volume of each surface.
25	Debugging level.
26	File with debugging info.
27-34	2D simulation parameters.

Table 3-4: A description of the `Surfsim` parameter file.

3.4 Summary

The advances in turbidite lobes modeling and strataform surface modeling are presented in this chapter. An automatic surface picks identification approach is illustrated as a preprocessor of turbidite lobes modeling. A serial of rules are proposed for turbidite lobe events modeling, including (1) global and local base levels modeling, (2) vertical and areal surface positioning, (3) well conditioning, (4) erosional events modeling and (5) stacking patterns reproduction. Several global coordinates transform approaches are applied in strataform surface simulation. Piecewise linear thickness trend can be honoured and inclined surface template is introduced to reproduce common strata correlation styles.

Chapter 4

Surface-based Facies Modeling

Facies modeling is the process of creating a discrete 3D facies distribution within a geological grid. Facies models are often cell based and focus on reproducing one- and two-point statistics, so complicated spatial structures are not often reproduced. As illustrated in Chapter 3, the proposed surface modeling approach may build complicated and geologically realistic surface models that honour available surface picks at wells. Therefore, utilizing the simulated surface models to capture curvilinear reservoir structures becomes a natural solution to introduce realistic curvilinear facies structures.

In this chapter, facies modeling is developed in the context of simulated surface models. Depositional trends information is utilized. Section 4.1 reviews the idealized deepwater turbidite facies distributions, which is the geological basis of the proposed approaches. Section 4.2 illustrates the approach for integrating geological concept models and 2D facies trends template. Section 4.3 presents facies modeling approaches that can integrate facies proportions. Section 4.4 presents a realistic case study.

4.1 Introduction

In terms of waning flow regime from bottom to top and with increasing path across a basin, turbidity current loses both energy and sediment; hence the distal turbidites, as well as deposits on the levees, do not show the complete turbidite sequences (Figure 4-1; Reineck and Singh, 1980). The resulting hypothetical facies plan distribution is shown in Figure 4-2. This is also the idealized facies distribution within a second-order turbidite lobe. The loss of energy results in progressively less basal erosion, deposition of progressively finer sediment and thickening of the finer part of the sandstone / mudstone couplet. Most importantly, accompanying the downcurrent (lateral) grading of size and bed thickness, there is a change in the internal structure of the sand component of the couplet, with progressively higher parts of the Bouma sequence forming the base of the turbidite bed (Figure 4-3; MacDonald, 1992). Based on above analysis, the idealized facies distribution of a second-order turbidite lobe is shown in Figure 4-4. Three facies are assumed in this diagram.
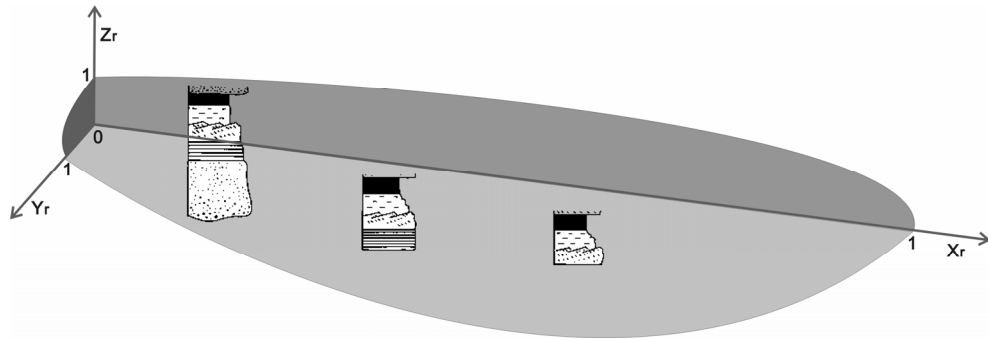
Figure 4-1: Schematic diagram depicting Bouma sequences change in terms of distance across basin and watering flow conditions (after Reineck and Singh, 1980). Background is a second-order turbidite lobe.
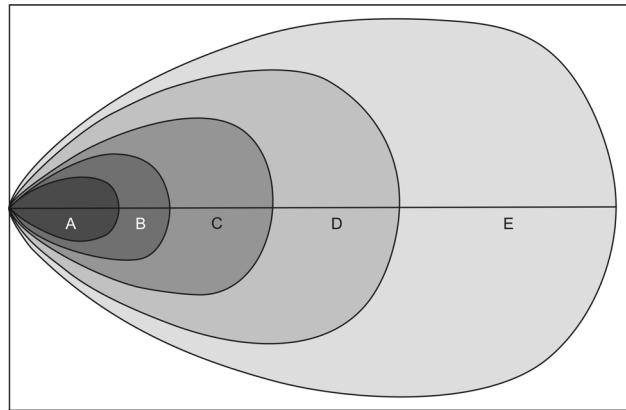
Figure 4-2: Hypothetical plan view showing geographic distribution of intervals in a flysch profile from Bouma division A at the base to E at the top (after Reineck and Singh, 1980).
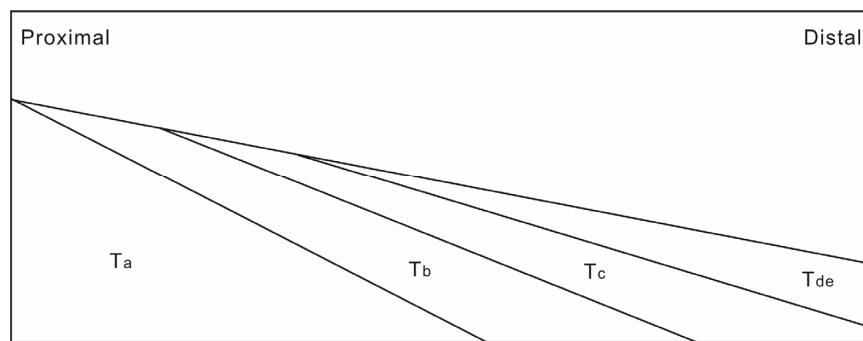
Figure 4-3: Schematic diagram showing upper parts of the Bouma sequence (Ta-Te) coming to rest on turbidite bed base distally (after MacDonald, 1992).
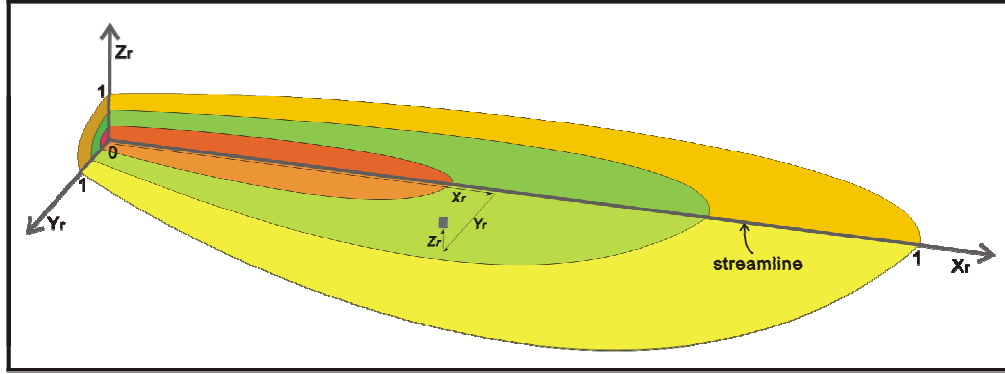
Figure 4-4: Schematic diagram depicting idealized facies distribution in a second-order turbidite lobe. This plot also shows how to calculate depositional coordinates for a given cell (after Pyrcz, 2004).

4.2 Surface-based facies proportion calculation

Facies models are often cell based. For a given cell, its depositional coordinates can be easily determined based on its vertical, longitudinal and transverse relative position within a second-order lobe. If facies trends are known, the position information may be transformed to facies proportions and taken into account in facies modeling process. Therefore, surface shape information will be transferred into facies modeling.

4.2.1 Integration of Geological Concept Models

The vertical facies trend may be available from well logs. Areal facies trend inference is difficult due to widely spaced wells. Therefore, an areal facies concept model is used often in practice. These conceptual models may come from experienced geologists. These models are problem specific and therefore no universal solutions exist. In this research, the areal facies distribution in Figure 4-2 is applied to illustrate the proposed methodology.

   There are several analytical turbidite lobe models available. One popular model is the "simple" lobe model proposed by Deutsch (2002). Assuming that the inner facies distribution follow the lobe boundary shape, the facies boundaries can be expressed as:

$$y_i = \begin{cases} w_i + 4 \cdot (W_i - w_i) \cdot [\frac{x}{2l}(1 - \frac{x}{2l})], & 0 \leq x \leq l \\[4mm] W_i \cdot \sqrt{1 - (\frac{x-l}{L_i - l})^2}, & l \leq x \leq L_i \end{cases} \tag{4.1}$$

where y_i is the Y coordinate of the distribution boundary of the ith facies, x is the X coordinate, and L_i is the maximum facies boundary length along centerline of lobe. An idealized areal facies distribution is shown in Figure 4-5.
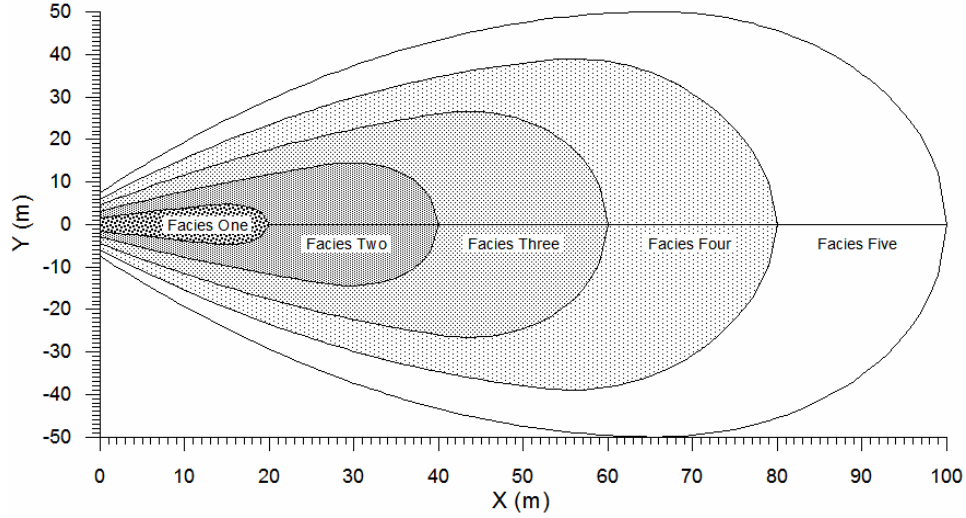
Figure 4-5: Schematic diagram illustrating the idealized facies distribution with Formula (12).

For a given cell on a lobe base, its depositional coordinates may be denoted as Xr, Yr and Zr. It may have the same vertical trend as some location on the centerline. The location can be inferred under some assumptions. Therefore, the 3D facies trend calculation problem can be simplified to a 2D problem. One convenient assumption is that for any point on axis, it has the same facies changing rate longitudinally and laterally (Figure 4-6), that is,

$$\frac{X_1}{X_2} = \frac{Y_1}{Y_2} = \frac{Y_1}{1} \tag{4.2}$$

where Y_1 is the distance from P_1 to its perpendicular projection on centerline, A; Y_2 is the lateral facies width of Facies Two from A; X_1 is the distance from A to P_2, the position has same vertical facies trend as P_1; and X_2 is the longitudinal distance from A to the boundary of Facies Two.

A linear vertical facies trend model may be applied to simulate the facies change proximally according to proximity theory. For convenience, the facies trend is defined in relative scale. Since the areal lobe shape is known, only vertical trend definition is needed in facies proportion calculation. An example linear vertical trend template is shown on the left plot in Figure 4-7.

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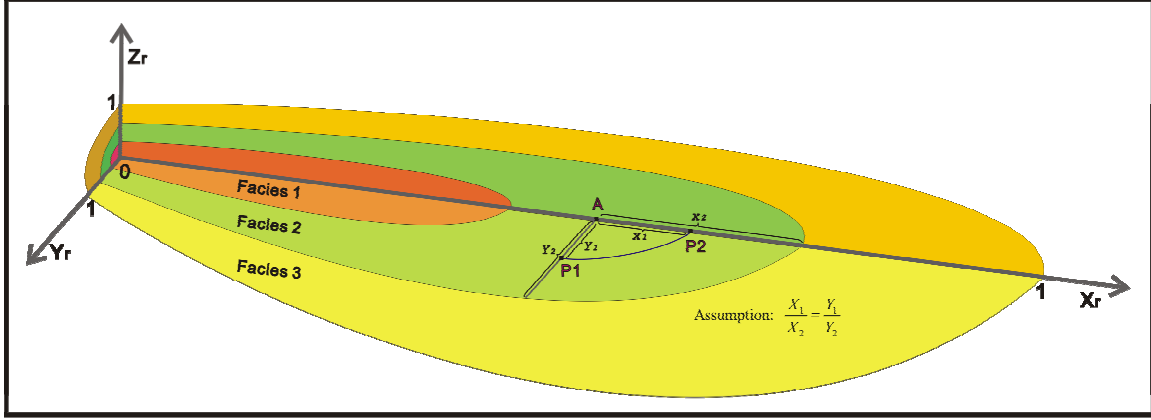
Figure 4-6: Schematic diagram illustrating the axis relative position determination procedure.
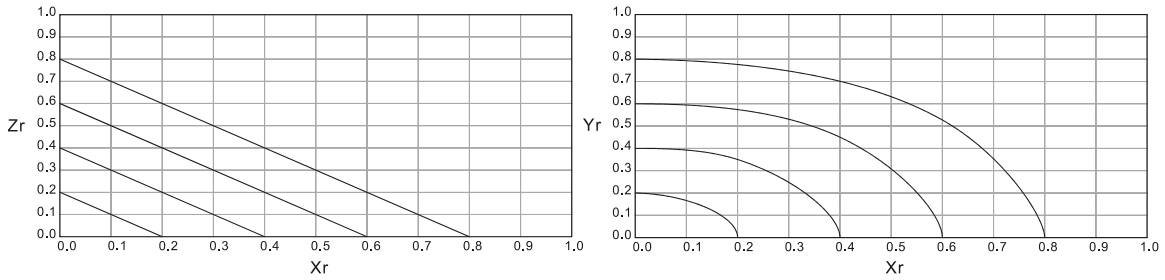
Figure 4-7: Schematic diagrams illustrating the linear and elliptical axis-vertical facies trend definition.

The calculated facies proportions may be rescaled to honour global proportions,

$$p_k^{1D}(z_r) = P_k \cdot p_k(z_r) \qquad (4.3)$$

where k denotes for the kth facies, $p_k^{1D}(z_r)$ is the updated facies proportion, P_k is the global proportion, and $p_k(z_r)$ is the calculated facies proportion.

4.2.2 Integration of Statistical Trends

When well spacing is close enough, areal facies trends may be inferred. In this case, both areal and vertical facies trends may be applied. For simplification, both vertical and areal facies trends are defined in relative scale. An elliptical areal facies trend and a linear vertical facies trend are applied in this thesis. The elliptical shape is selected because it is simple and the facies distribution follows the shape of the lobe outline very well (Figure 4-8). An example 2D trend template is shown in Figure 4-7.

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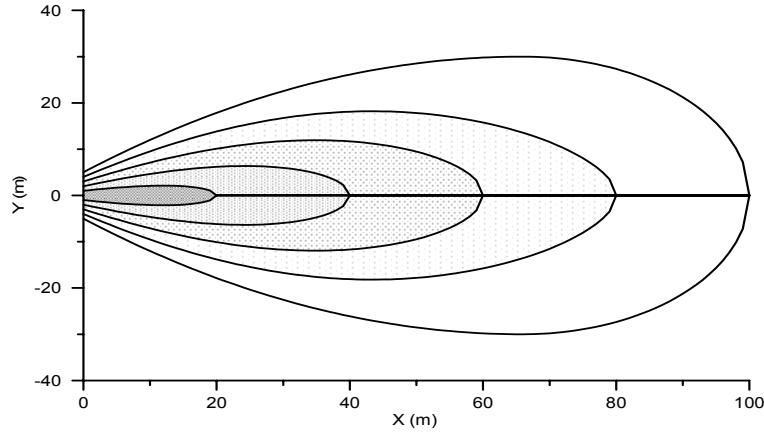
Figure 4-8: An analytical diagram showing the areal facies distribution with elliptical areal facies trends.

Under the assumption that the areal and vertical facies trends are conditionally independent, the final facies trend may be expressed as,

$$p_k^{CI}(y_r, z_r) = P_k \cdot p_k(y_r) \cdot p_k(z_r) \qquad (4.4)$$

where k denotes for the kth facies, $p_k^{CI}(y_r, z_r)$ is the updated facies proportion under conditional independent assumption, P_k is the global proportion, and $p_k(y_r)$ and $p_k(z_r)$ are the calculated areal and vertical facies proportions, respectively.

A common shortcoming of the conditional independence assumption is that the high values may be extremely high and low values may be extremely low (Deutsch, 2002). To overcome this shortcoming, the permanence ratio approach (Journel, 2002) is applied to integrate the two types of trends,

$$p_k^{PR}(y_r, z_r) = \dfrac{\dfrac{1 - P_k}{p_k}}{\dfrac{1 - p_k}{p_k} + \dfrac{1 - p_k(y_r)}{p_k(y_r)} \cdot \dfrac{1 - p_k(z_r)}{p_k(z_r)}} \qquad (4.5)$$

where $p_k^{PR}(y_r, z_r)$ is the updated facies proportion under permanence ratios assumption.

The calculated facies proportions are also scaled to honour global facies proportions.

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4.3 Application of Facies Proportions

Programs available in the public domain to integrate calculated facies proportions include `GTSIM`, `BlockSIS` and `sisim_lm`. `GTSIM` applies facies proportions directly to truncate continuous Gaussian values. `BlockSIS` and `sisim_lm` integrate facies proportions as secondary data.

For surface-based facies modeling, both facies types and facies proportions are known, so the corresponding Gaussian value may be easily calculated by reverse transformation the centroid *ccdf* value of the facies (Figure 4-9). A Fortran 90 program, `CalcSgsData`, was written to perform the proposed methodology. The program parameters are shown below; the description of each parameter is included in Table 4-1.
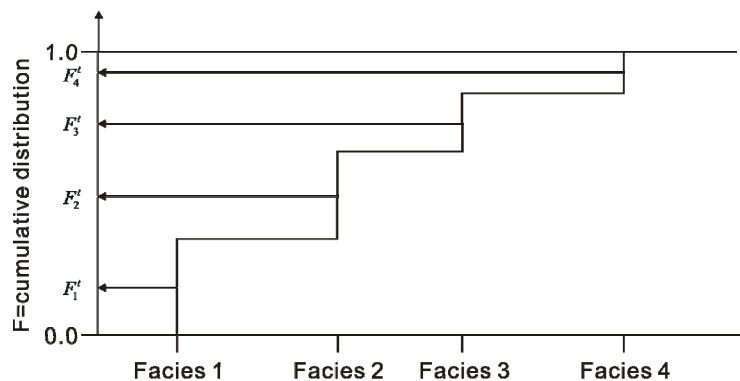
Figure 4-9: Schematic diagram illustrating the *ccdf* value of each facies.

```
Parameters for CalcSgsData:

1. well.dat                              - well file
2. 1 2 3 4 5                             - Columns for keyout, x, y, z, facies
3. lm.out                                - local mean file
4. upwell.dat                            - output file
5. 4                                     - number of facies
6. 130    25.0    50.0                   - nx,xmn,xsiz
7. 130    25.0    50.0                   - ny,ymn,ysiz
8. 280     0.5     1.0                   - nz,zmn,zsiz
```

Line	Description
1	Input file with wells data. The file should be in GeoEAS format.
2	Column numbers for the keyout array, x, y, z location and facies code.
3	Input file with facies proportions / local means data.
4	The file with updated wells data. An additional column with the transformed Gaussian values is added.
5	The number of facies.
6-8	The regular grid definition.

Table 4-1: A description of the `CalcSgsData` parameter file.

A comparison of above transformation approach and conventional transformation approach is shown in Figure 4-10. Although the transformed values do not have perfect Gaussian shape, they

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are consistent with the facies proportions. A typical `GTSIM` workflow with facies proportions is shown in Figure 4-11. The `GTSIM` program was modified to have the ability to read keyout array, so the volume out of the bounding surfaces will not be modeled. If a cell is located within the strata, its keyout value equals to 1; otherwise it equals to 0. An example `GTSIM` parameter file is shown below and each parameter is included in Table 4-2.
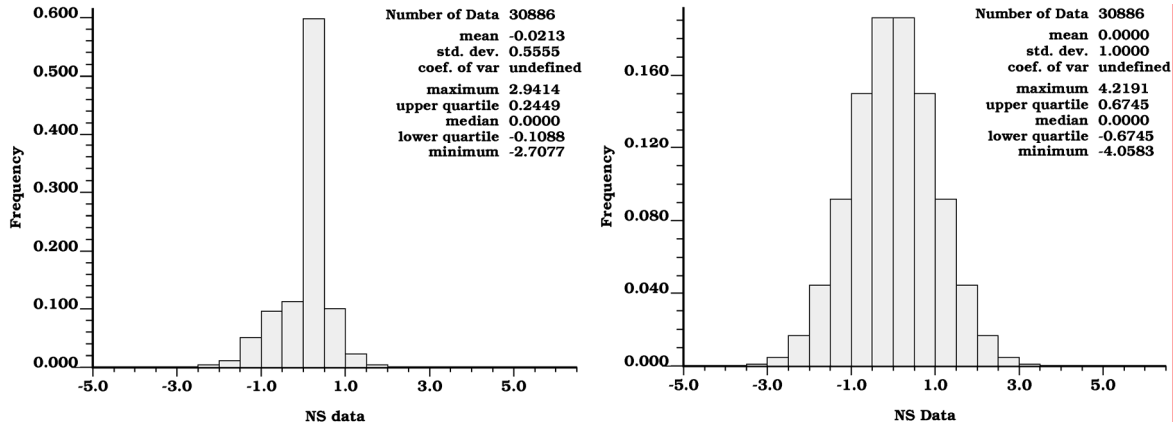

Figure 4-10: Comparison of calculated Gaussian values with `CalcSgsData` and conventional Normal score transformed Gaussian values. Left: `CalcSGSData`; right: `nscore`.

```
Parameters for GTSIM:

1.  sgsim.out                   - input file with Gaussian values
2.  gtsim.out                   - output file with categorical values
3.  1                           - number of realizations
4.  50   50   1                 - nx,ny,nz
5.  3                           - number of categories
6.  1    0.25                   - cat(1) - global proportion(1)
7.  2    0.25                   - cat(2) - global proportion(2)
8.  3    0.50                   - cat(3) - global proportion(3)
9.  1                           - proportion curves (0=no, 1=yes)
10. propc.dat                   - file with local mean values
11. 1  2  3  4                  - keyout, column number for p1,p2,p3...
```

Line	Description
1	Input file with Gaussian values. The file should be in GeoEAS format.
2	Output file with categorical values. The file should be in GeoEAS format.
3	Number of realizations
4	Total grid number in x, y, z directions.
5	Number of categories.
6-8	Global proportions of each category. The total lines equal to the number of categories.
9	Indicator for using proportion curves, 0 – no, 1 – yes.
10	If proportion curves are used, the file with the proportion curves needs to be specified here.
11	The columns for keyout array, probability for each category.

Table 4-2: A description of the `GTSIM` parameter file.
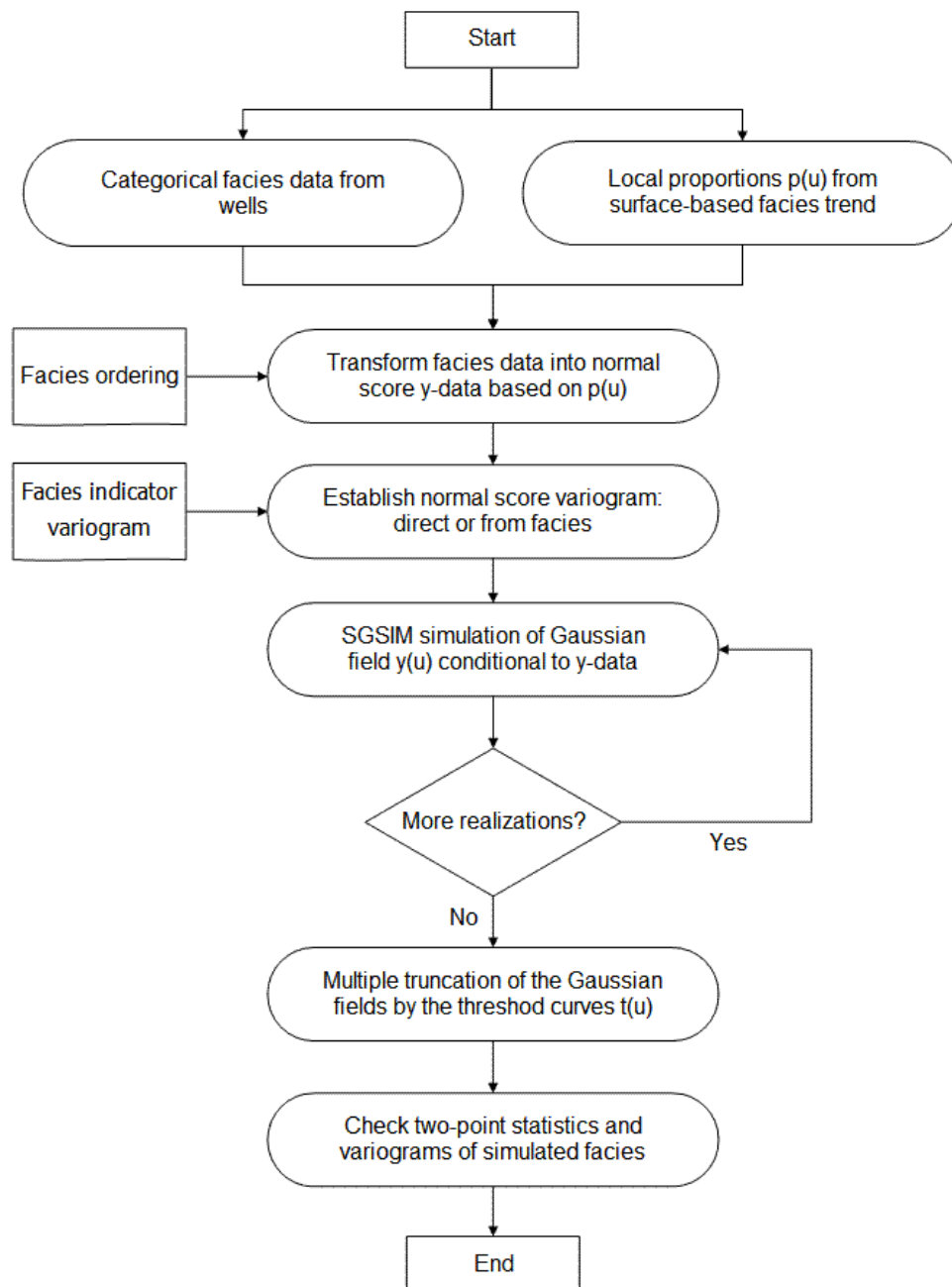
Figure 4-11: Schematic diagram illustrating the workflow of `GTSIM` with facies proportions.

There are two algorithms that can integrate facies proportions as secondary data. One is the non-stationary simple kriging with residuals from the locally varying mean probabilities,

$$i^*_{LVM_1}(\mathbf{u};k) - p_k(\mathbf{u}) = \sum_{\alpha=1}^{n} \lambda_\alpha^{SK}(\mathbf{u};k) \left[i(\mathbf{u}_\alpha;k) - p_k(\mathbf{u}_\alpha) \right] \qquad (4.6)$$

Another one uses one minus the sum of the weights assigned to the local mean,

$$i^*_{LVM_2}(\mathbf{u};k) = \sum_{\alpha=1}^{n} \lambda_\alpha^{SK}(\mathbf{u};k) i(\mathbf{u}_\alpha;k) + \left[1 - \sum_{\alpha=1}^{n} \lambda_\alpha^{SK}(\mathbf{u};k) \right] p_k(\mathbf{u}) \qquad (4.7)$$

When the locally varying mean values are smooth, the differences between Function (4.6) and (4.7) are minor (Deutsch, 2006).

`sisim_lm` program is not recommended for it cannot utilize the keyout array; therefore, the volume above the top surface or below the base surface will be filled up with background facies.

4.4 Synthetic Case Study

In this section, a case study will be presented to illustrate the surface-based facies modeling approach. The case study aims at illustrating and comparing two common facies modeling techniques, `GTSIM` and `BlockSIS`, by integrating the same facies proportions model. Only one surface model and facies proportions model was built. The global coordinates have been rotated to parallel to stratigraphic framework. Within the 5 Kilometers by 5 Kilometers study area, 81 vertical wells are equal-distance sampled (Figure 4-12). A long section and a cross section are shown in Figure 4-13 to illustrate the reservoir spatial structures.

Lobe geometry is the most important control on facies distribution. When areal and vertical facies trends can be inferred, facies proportions can be calculated using the developed methodologies. Four facies types are assumed in this case study, which represent the typical facies components of Bouma sequence (Figure 4-14). They are summarized in Table 4-3. Declustering may be applied to estimate the global facies proportions (Figure 4-15).
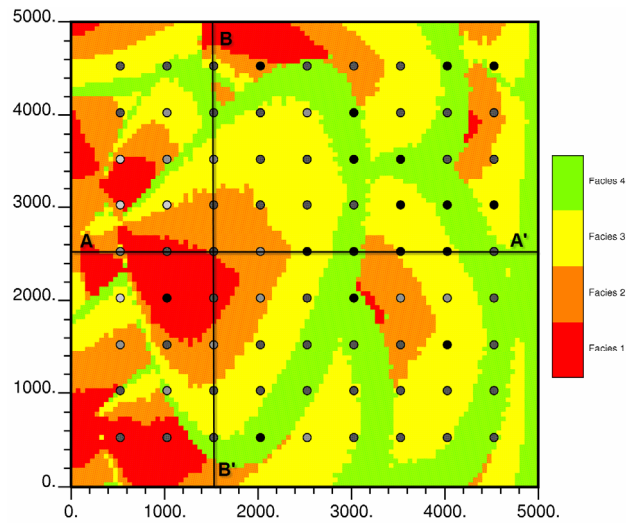
Figure 4-12: The surface distribution on base surface and the location map of 81 vertical synthetic wells. The position of a long section (A-A') and a cross section (B-B') are also marked.
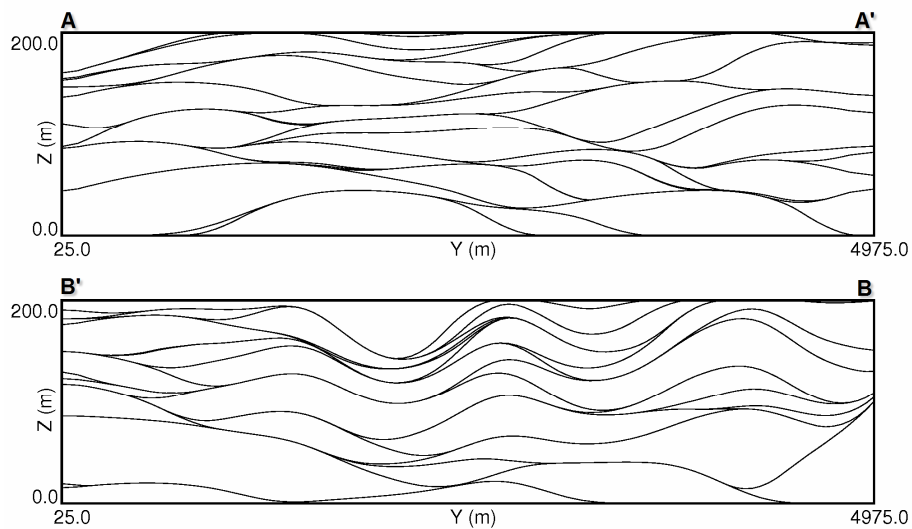

Figure 4-13: The long section A-A' and cross section B-B' to illustrate the reservoir spatial structures.

	Grain Size	Divisions	Interpretation
	Mud	E Laminated to homogeneous mud	Low density tail of turbidity current
	Silt	D Upper mud/silt laminae	Shear sorting of grains & flocs
	Sand	C Ripples, climbing ripples, wavy or convolute laminae	Lower part of lower flow regime
		B Plane laminae	Upper flow regime - plane bed
	Coarse Sand	A Structureless or graded sand to granule	Non-equilibrium flow quick bed

Figure 4-14: Ideal sequence of sedimentary structures in a turbidite bed (after Pickering *et al*. 1989).

Category	Grain Size	Bedding	Bouma (1962) Divisions
Facies 1	Coarse Sand	Structureless or graded sand to granule	A
Facies 2	Sand	Plane laminae and ripples, climbing ripples, wavy or convolute laminae	B and C
Facies 3	Silt	Upper mud/silt laminae	D
Facies 4	Mud	Laminated to homogeneous mud	E

Table 4-3 A summary of the lithofacies definition used in the synthetic case study.
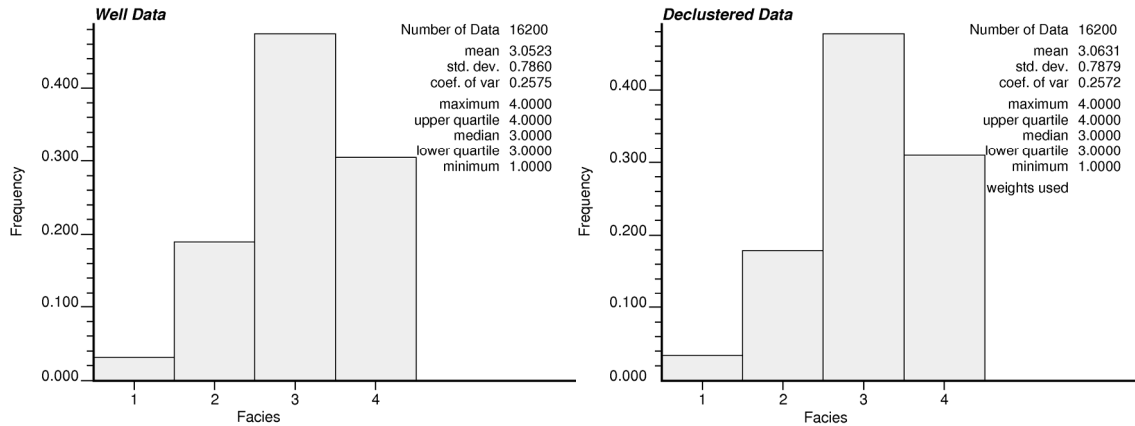

Figure 4-15: The distribution of original and declustered facies distribution from synthetic well logs.

4.4.1 BlockSIS

A SIS-based facies modeling approaches, `BlockSIS,` is applied first.

1. Variogram Calculation

Like other SIS-based facies modeling approaches, the variogram of each facies should be modeled to specify maximum facies continuity direction and range (Figure 4-16 and Figure 4-17). With many wells, variogram inference is straightforward. In practice, variogram inference may be a big challenge because (1) there are usually not so many densely sampled wells, and (2) strati-graphic framework is usually highly deformed.

2. Facies Modeling

A long section and a cross section of a facies model built with `BlockSIS` are shown in Figure 4-18. No image cleaning is performed in this case study for it may alter the spatial structure. Therefore, the facies model appears a little patchy.
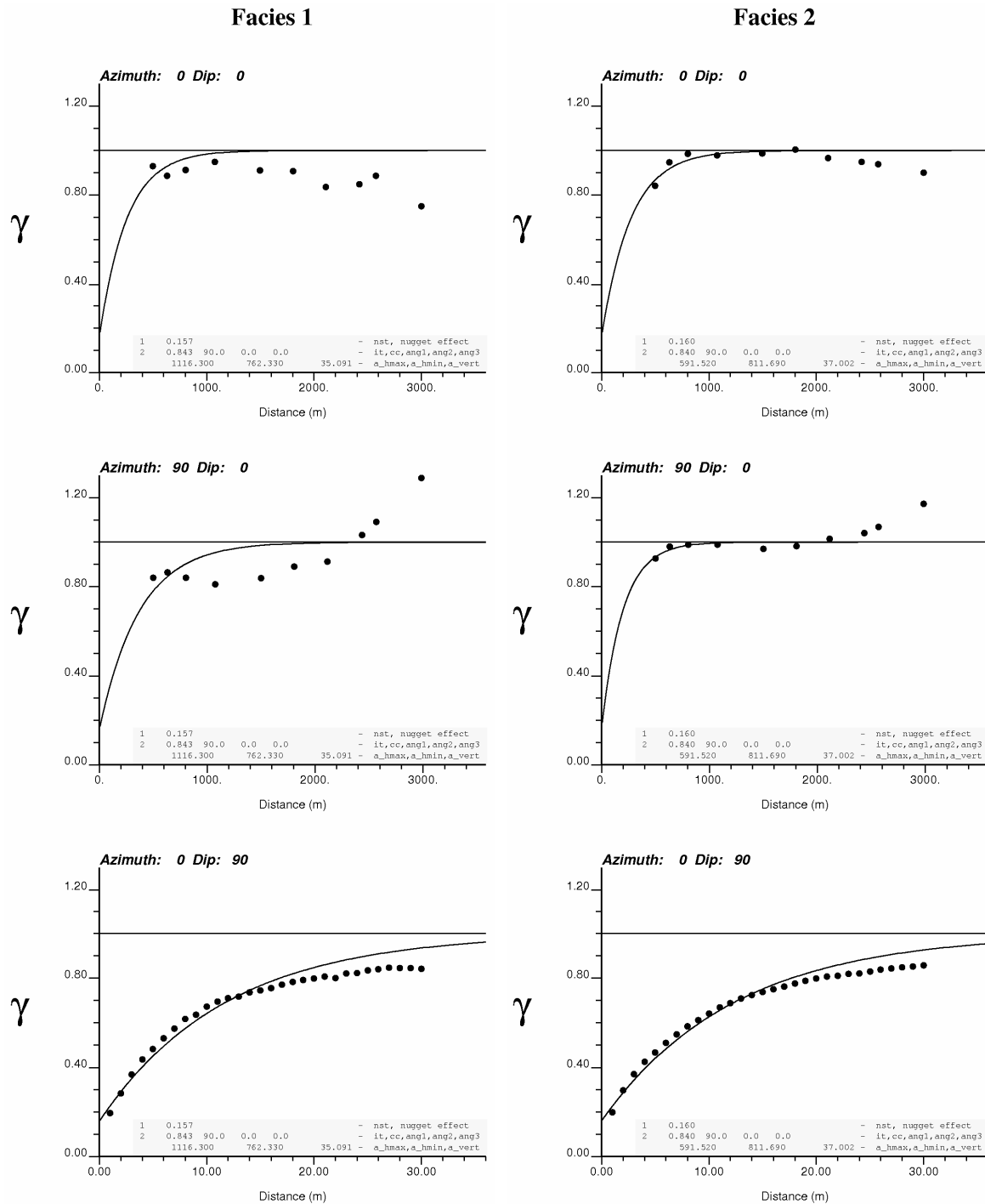
Facies 1

Facies 2

Figure 4-16: 3D Variograms of facies one and facies two.
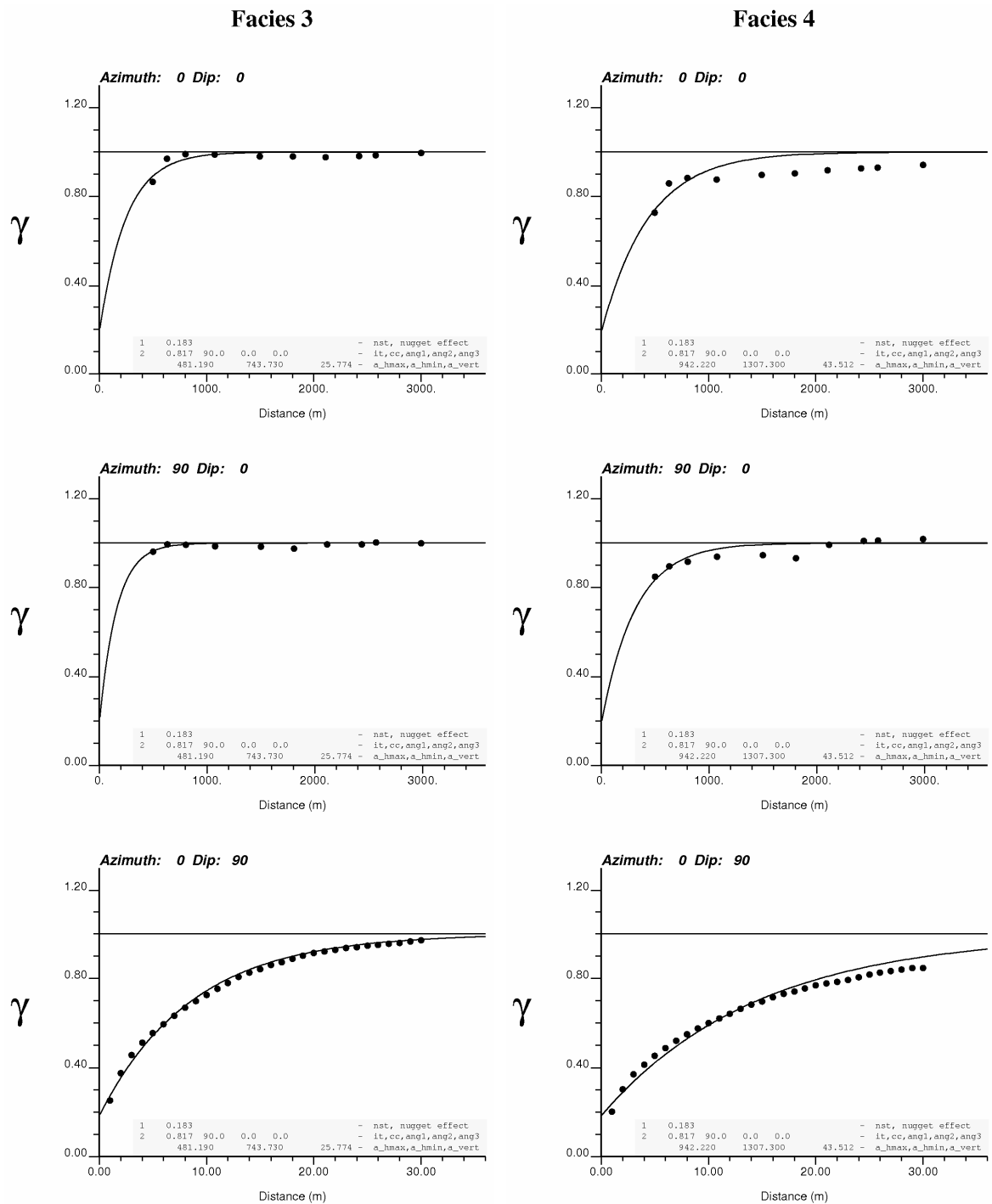
Facies 3

Facies 4

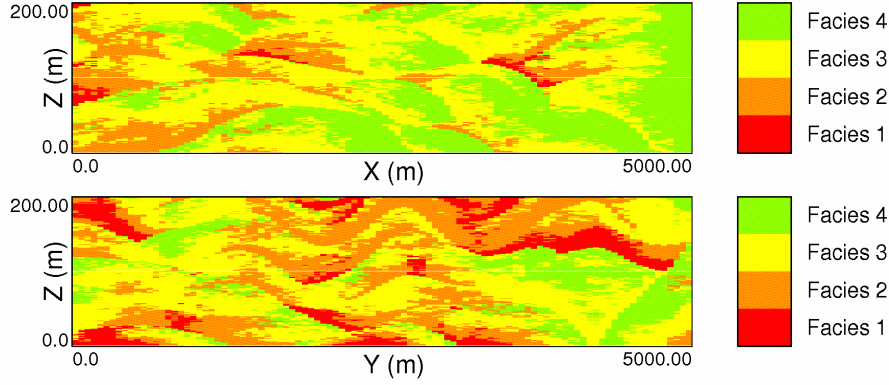**Figure 4-17:** 3D variograms of Facies Three and Facies Four.

Figure 4-18: A long section and a cross section illustrating the facies modeling results with `BlockSIS`. Above: long section; and below: cross section.

3. Model Validation

The histogram reproduction of `BlockSIS` is shown in Figure 4-19. The histogram reproduction is very good.

Each indicator variogram is checked (Figure 4-20 and Figure 4-21). Short-scale variation is well reproduced, but long-scale structure is not well captured, especially in the vertical direction. In general, the variogram reproduction is very good.

A quantitative measure of closeness to the true probabilities may be calculated with,

$$C = \frac{1}{N} \sum_{i=1}^{N} \{ p(u;k) \mid true = k \} \tag{4.8}$$

This measure is interpreted as the average predicted probability of the true facies. *C* value describes how "right" the probabilities are for the true facies. The limitation of *C* is that it gives no credit when a similar facies is predicted nor does it penalize the case when drastically different facies are predicted (Deutsch, 2002). In this case study, the *C* value is 0.3355 with `BlockSIS` approach.

Another indicator is the local probabilities. The local probabilities are "accurate" or "fair" if they accurately reflect the true fraction of the predicted facies occurs (Deutsch, 2002). Cases where the actual fraction departs significantly from the predicted probabilities are a problem. The corresponding accuracy plots are shown in Figure 4-22. The accuracy is very good.

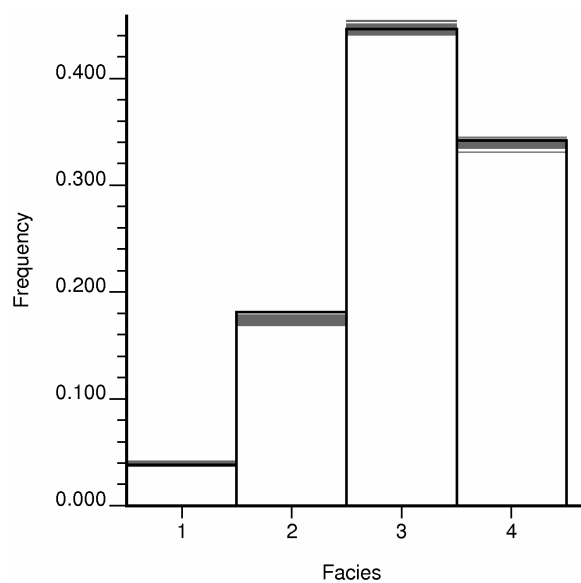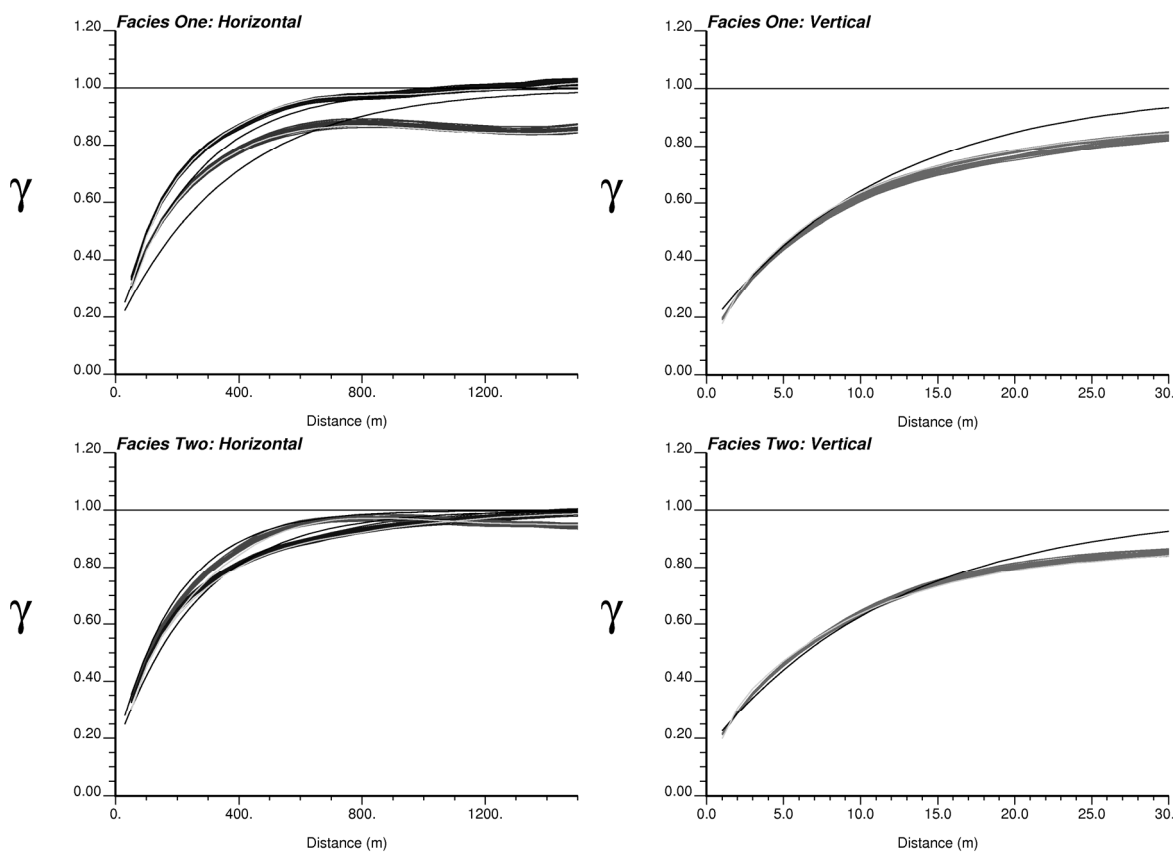**Figure 4-19:** Histogram reproduction of 25 realizations.
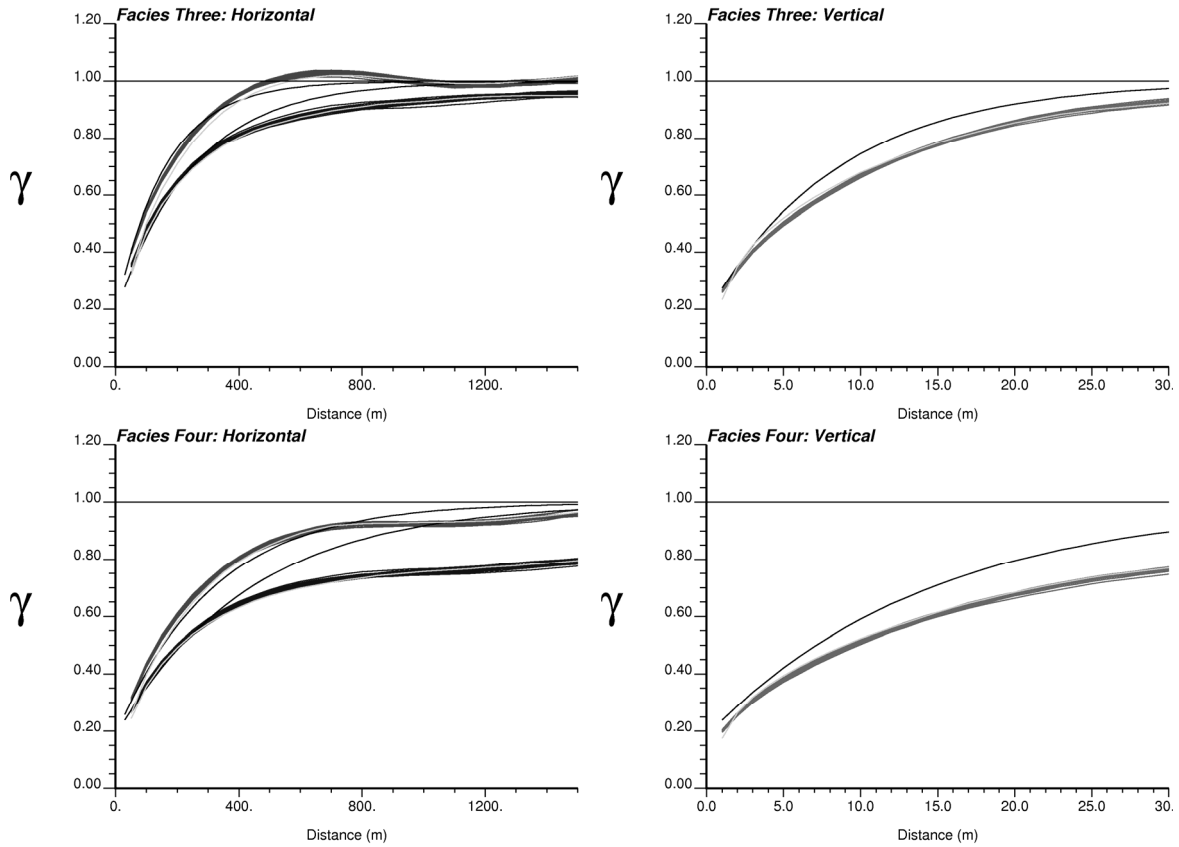

Figure 4-20: Variogram reproduction of Facies One and Two.

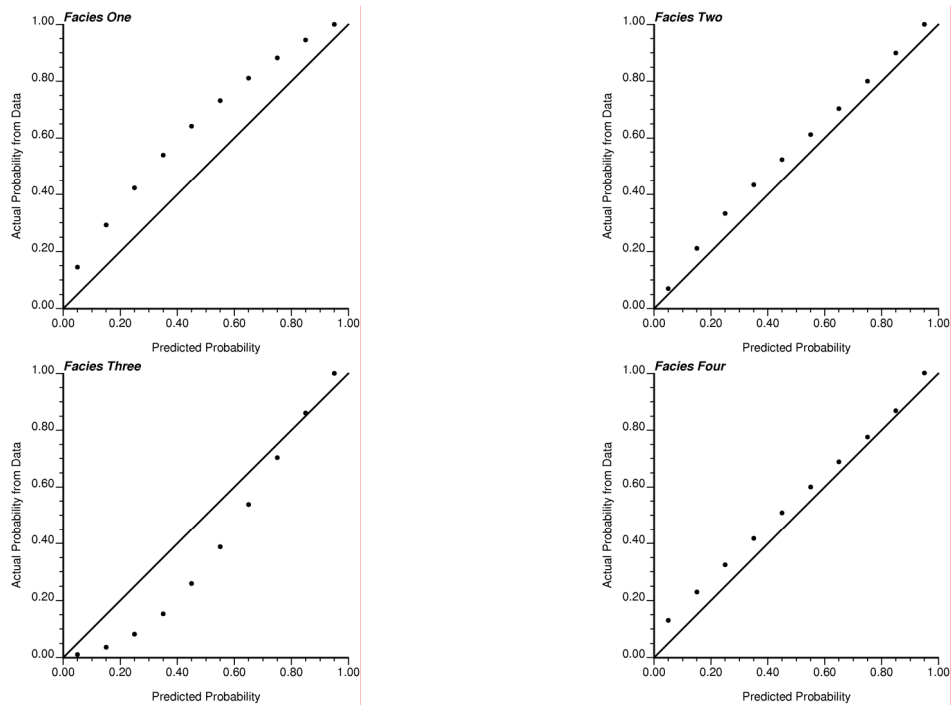**Figure 4-21:** Variogram reproduction of Facies Three and Four.

Figure 4-22: Accuracy plots of four facies.

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4.4.2 GTSIM

1. Normal Score Transform

As mentioned earlier, conventional normal score transform is not appropriate when local proportions are available. `CalcSGSData` program is applied to transform facies data to normal score values (Figure 4-23).
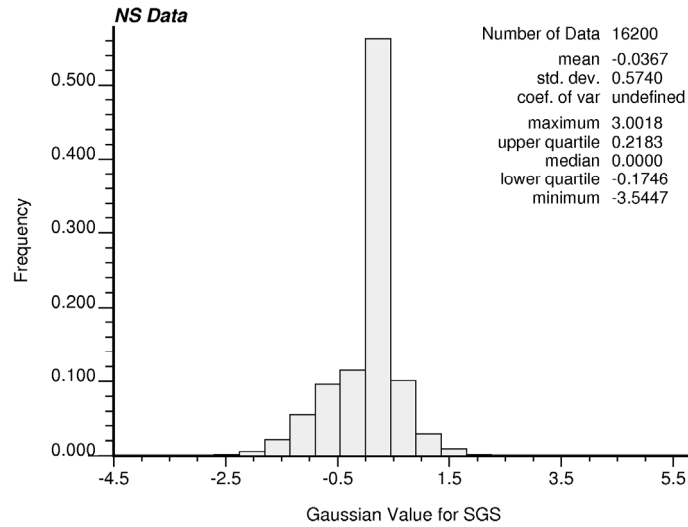
Figure 4-23: The normal score transformed facies data based on collocated facies proportions. A high spike exists.

2. Variogram Calculation

Truncated Gaussian simulation requires a single variogram for the normal score transformed facies variable. In general, it is not a good idea to directly calculate and fit the transformed facies variogram for the spikes. The recommended approach is to:

- Take the most important indicator variogram.
- "Invert" it numerically by `bigaus2` program to the corresponding normal score variogram (Figure 4-24).
- Fit the normal score variogram to get input variogram model (Figure 4-25)

The fitted Gaussian variogram is more parabolic at short distances compared with the original variogram.

3. Facies Modeling

The advantage of `GTSIM` is that the simulated facies model is very clean. The spatial structure is well honoured (Figure 4-26).

Figure 4-24: The results of `bigaus2` transform. The dash lines show the input indicator variograms and solid lines show the transformed variogram.
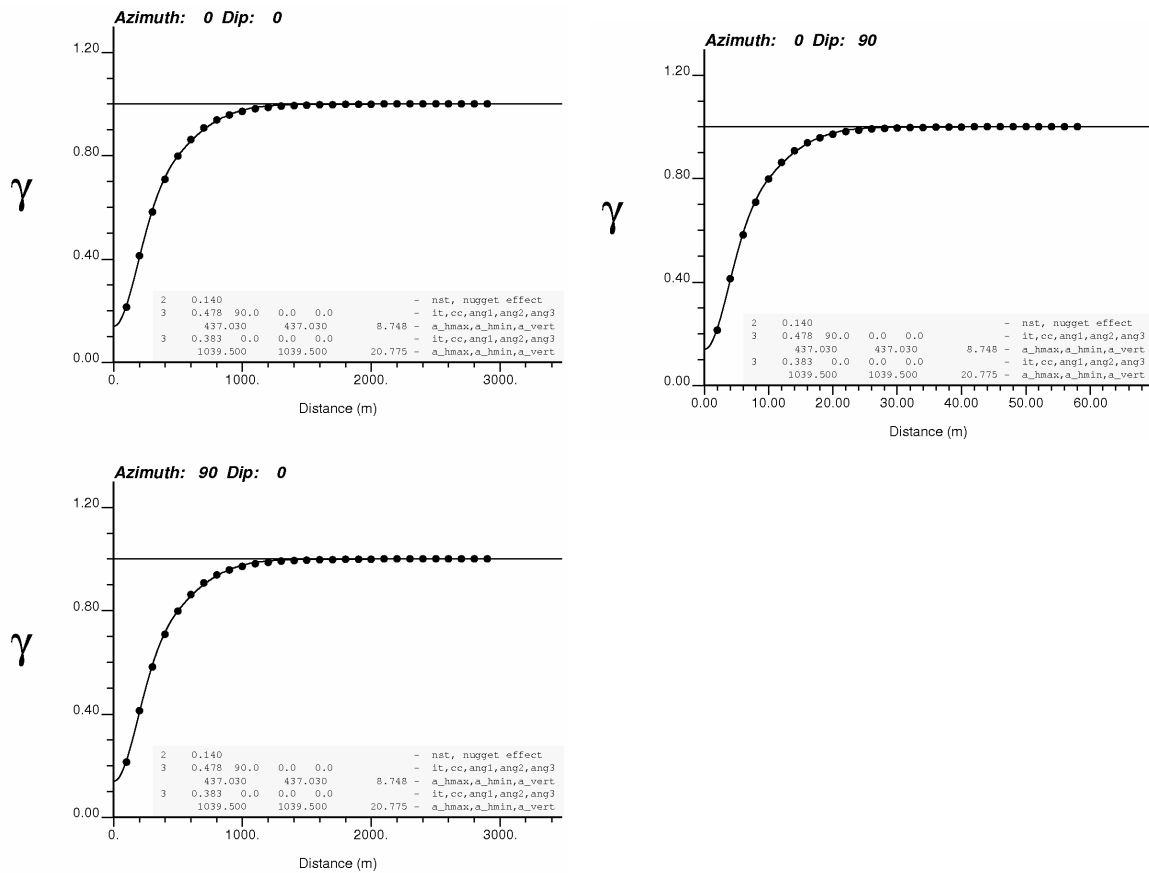
Figure 4-25: The fitted Gaussian model of the `bigaus2` variogram.
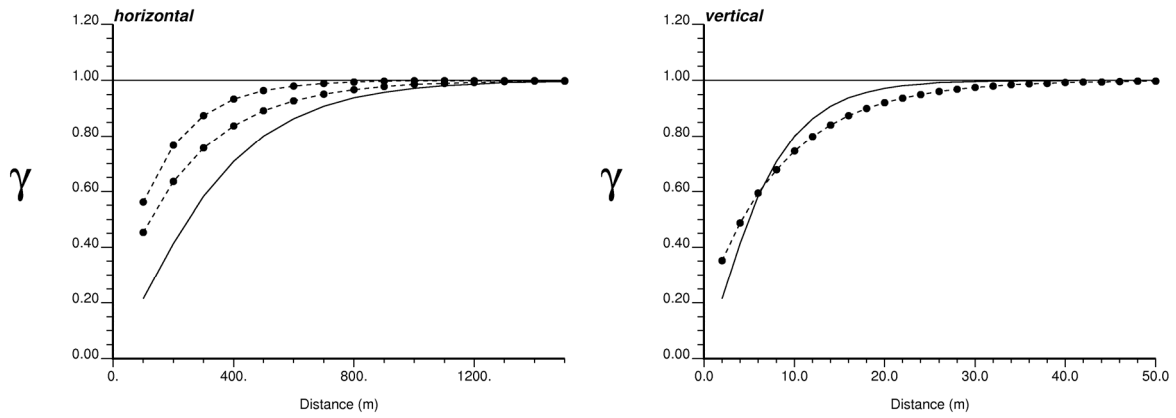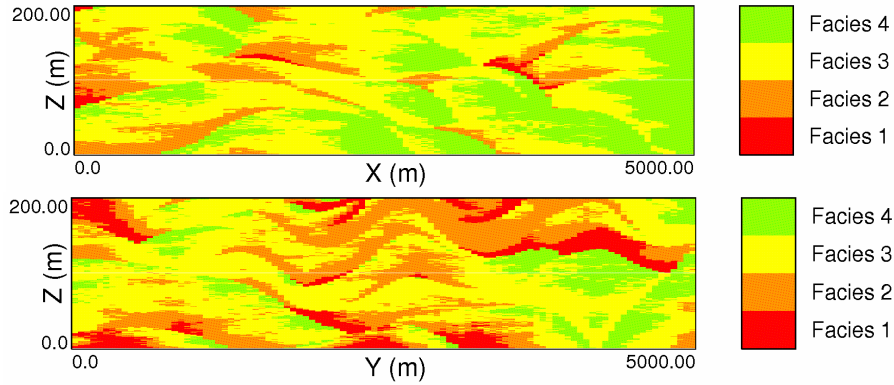
Figure 4-26: The long and cross sections of a truncated Gaussian realization. Above shows the long section and below shows the cross section.

4. Model Checking

The histogram reproduction of 25 realizations is shown in Figure 4-27. The lowest facies proportion (Facies One) is reproduced very well. In general, the histogram reproduction is very good, but it is not as good as `BlockSIS`.

For `GTSIM`, the input variogram is the normal score variogram. Therefore, the variogram of the simulated Gaussian models were checked, instead of indicator variograms of facies models (Figure 4-28). In general, the variograms are very close to the input.

The *C* value is the same as `BlockSIS`, 0.3355, in this case study.

The accuracy plots are made on the by-facies basis (Figure 4-29). Accuracy plots show it is better than `BlockSIS`.
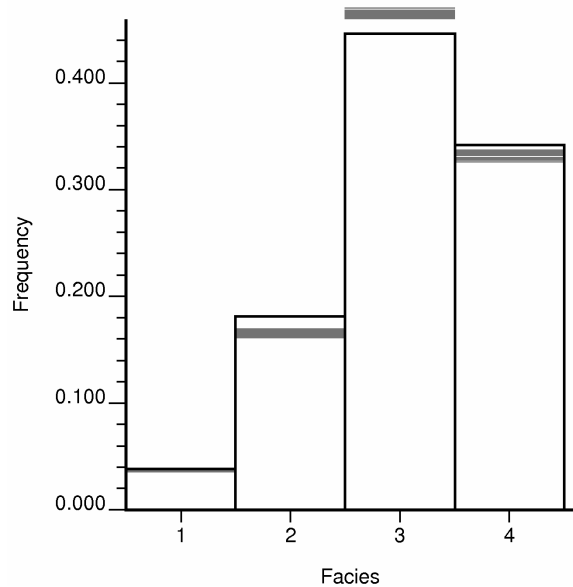
Figure 4-27: The histogram reproduction of 25 `GTSIM` realizations.

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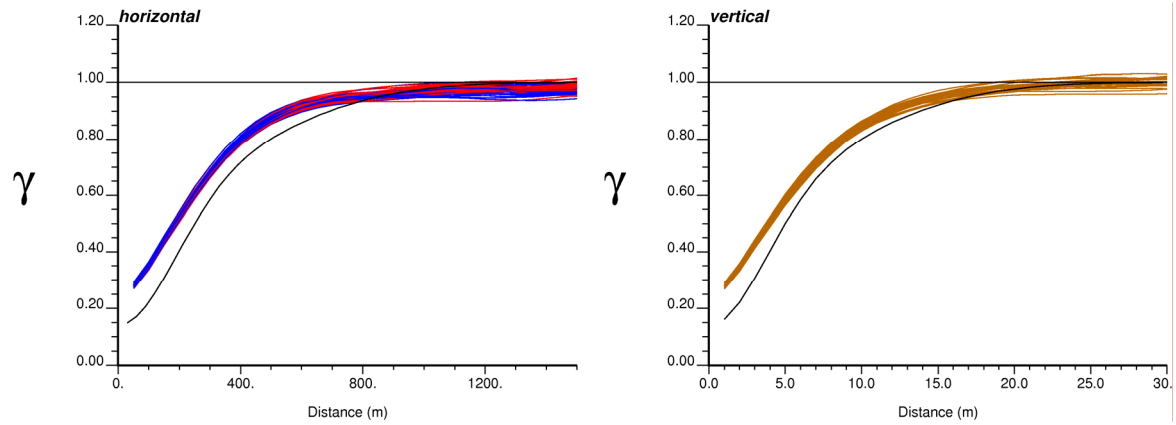
Figure 4-28: The variogram reproduction results of 25 GTSIM realizations.
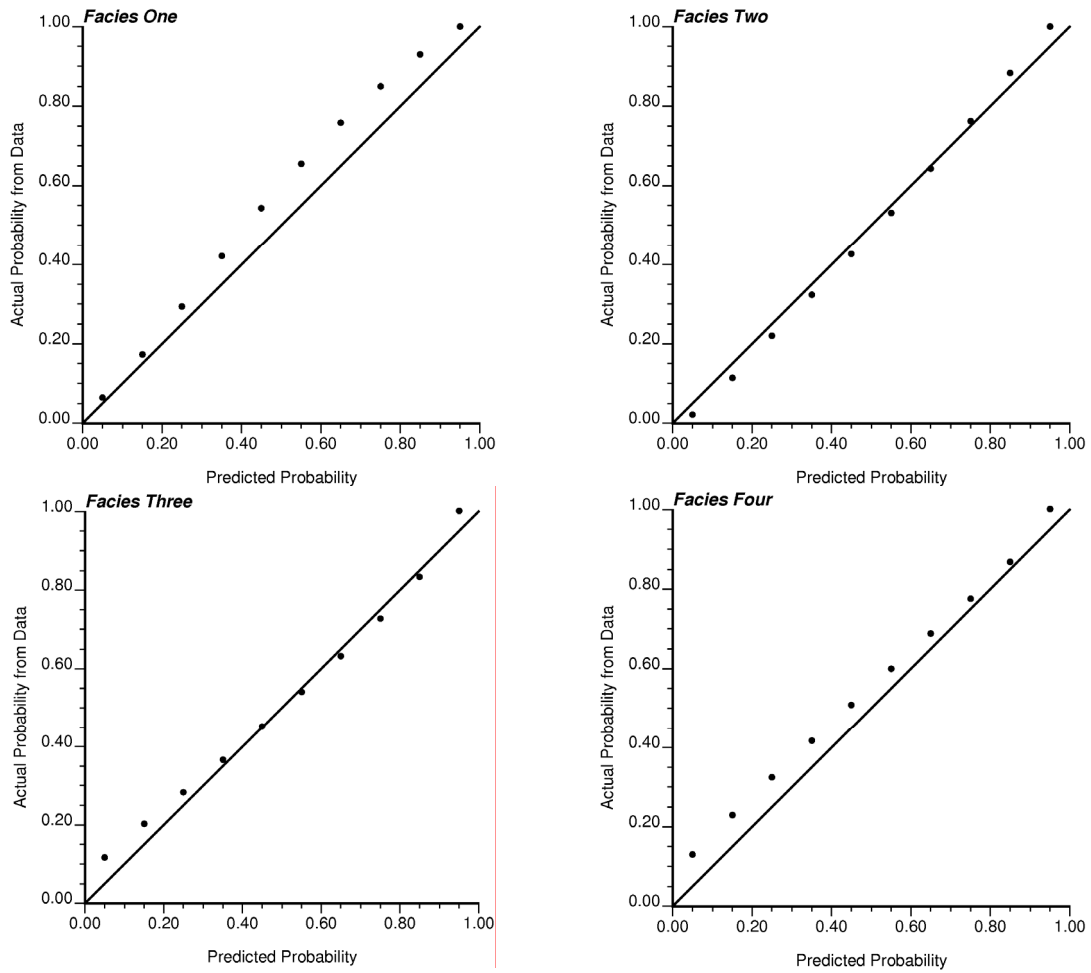
Figure 4-29: Accuracy plots of four facies.

4.4.3 Conclusions

Comparing the simulated facies model and model checking results, the following conclusions can be drawn:

1. The facies model of truncated Gaussian simulation is cleaner. For deepwater turbidite systems, the facies correlation is very strong; therefore, truncated Gaussian simulation approach appears more suitable.

2. In general, both simulation approaches honour well data and spatial structures. `Block-SIS` shows short-scale spatial variability.

Chapter 5

Surface-based Turbidite Modeling Case Study

In this chapter, the application of stochastic surface-based simulation to a synthetic turbidite reservoir is demonstrated.

5.1 The Data

The bounding surfaces were synthetically constructed. The slope gradient is about 2 degrees, which is common in distal continental slope environment. The stratum is roughly 60m (198ft) thick and pinches out towards west and north (Figure 5-1, Figure 5-2). The initial bathymetry is a northwest-southeast-trending submarine depression, and it is assumed that 36 vertical wells are available (Figure 5-3). 36 wells are chosen as a reasonable high level of conditioning in a typical deepwater reservoir study. The 36 wells are regularly distributed (1000 m). A large amount of wells are used in this case study for better variogram inference and enough well data for controlling facies, porosity and permeability distributions. As we discussed earlier in Chapter 3, the newly developed dual spline error surface interpolation approach works efficient with a relatively large number of wells. All available data will be honoured, including well picks, facies, porosity and permeability at wells. No large-scale seismic trend and areal trend are applied.

The turbidite reservoir is dominated by compensational cycles that constrain the distribution of lithofacies. Facies along wells were sampled from an unconditional SIS-based realization for modelling the facies distribution at wells. Four facies types are recognized (Table 5-1, Figure 5-4) and linear vertical facies trend is assumed from proximal to distal based on proximity theory. Declustering technology is applied to rebuild global facies distribution (Figure 5-5). In this synthetic case study, the "true" facies model is assessable, so we know the "real" facies proportions.

Porosity and permeability along the wells were synthetically sampled on a by-facies basis. Permeability is commonly related to porosity. For simplicity, an experimental logarithm relationship between porosity and permeability is applied to build the porosity-based permeability distribution (Deutsch, 2002). The regression equation takes the form:

$$log(K)^* = a_0 + a_1 \cdot \phi \qquad (5.1)$$

where $log(K)^*$ is the predicted logarithm of permeability, a_0 and a_1 are regression coefficients, and ϕ is porosity.

The reservoir is assumed to be a mud-rich turbidite fan. Therefore, mudstone is the most important facies component under this geological background. Porosity and permeability have typi-

cal bimodal distribution (Figure 5-6). The scatter plots of permeability and porosity are shown in Figure 5-7.
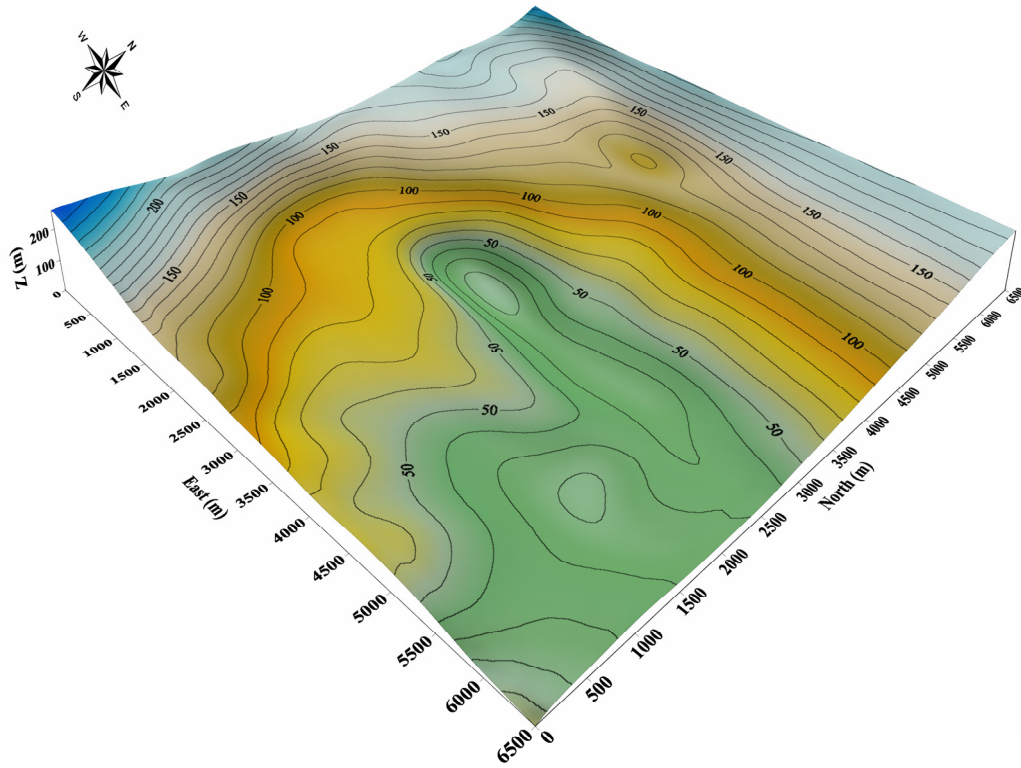
Figure 5-1 The initial bathymetry for the synthetic case study. The contour lines show the elevation distribution of the base surface.
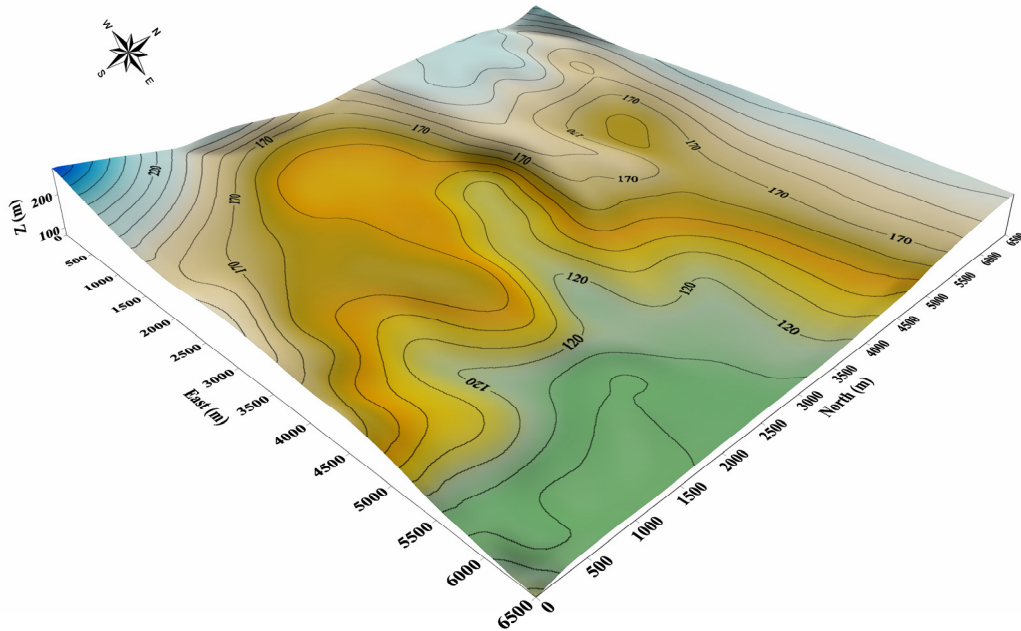
Figure 5-2 The terminal bathymetry for the synthetic case study. The contour lines show the elevation distribution of the top surface.
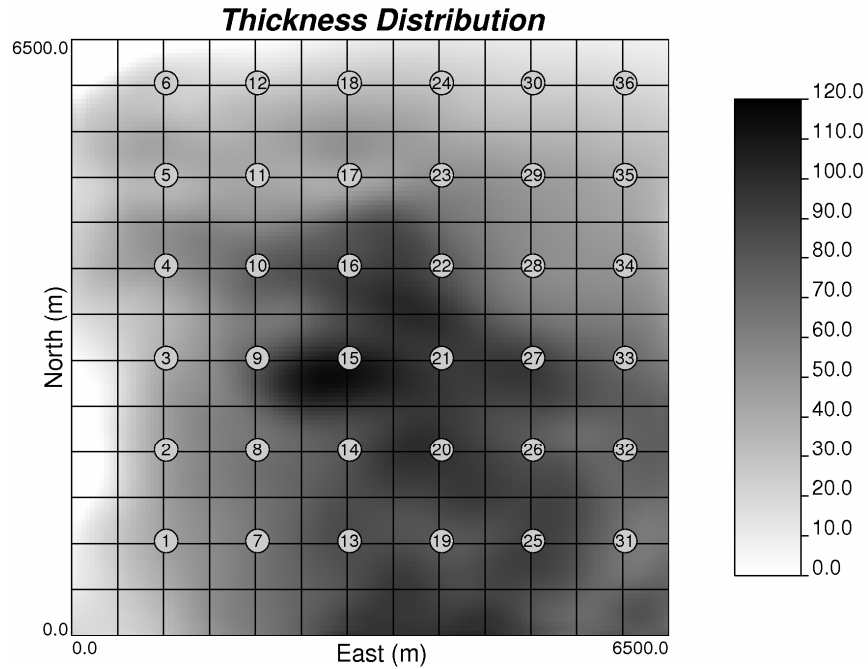
Figure 5-3 The thickness distribution of the strata and the well positions of 36 synthetic wells.

Category	Dominant Lithology	Bedding	Bouma Sequence
Facies 1	Sandstone	Thick – massive, crudely graded	A-division
Facies 2	Sandstone	Thin – medium, subtly graded	B, C-division
Facies 3	Siltstone	Thinly bedded siltstone	D-division
Facies 4	Mudstone	Devoid of mudstone	E-division

Table 5-1: A summary of the lithofacies defined in this case study.
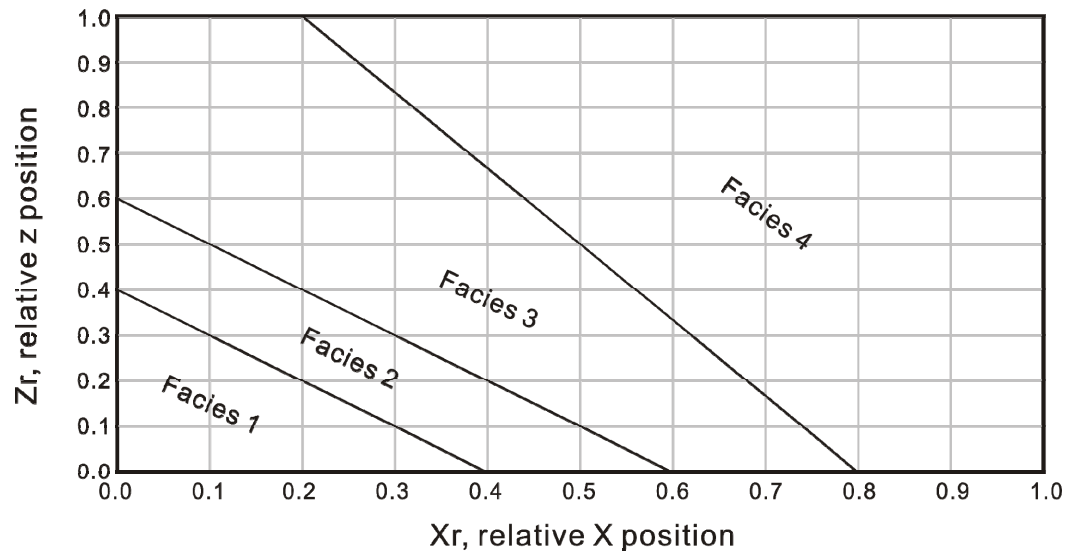
Figure 5-4 The axis-vertical trend definition. The distance is measured in relative scale, and linear facies transitions are assumed. Xr is the relative position along main streamline; Zr is the relative position along vertical direction.
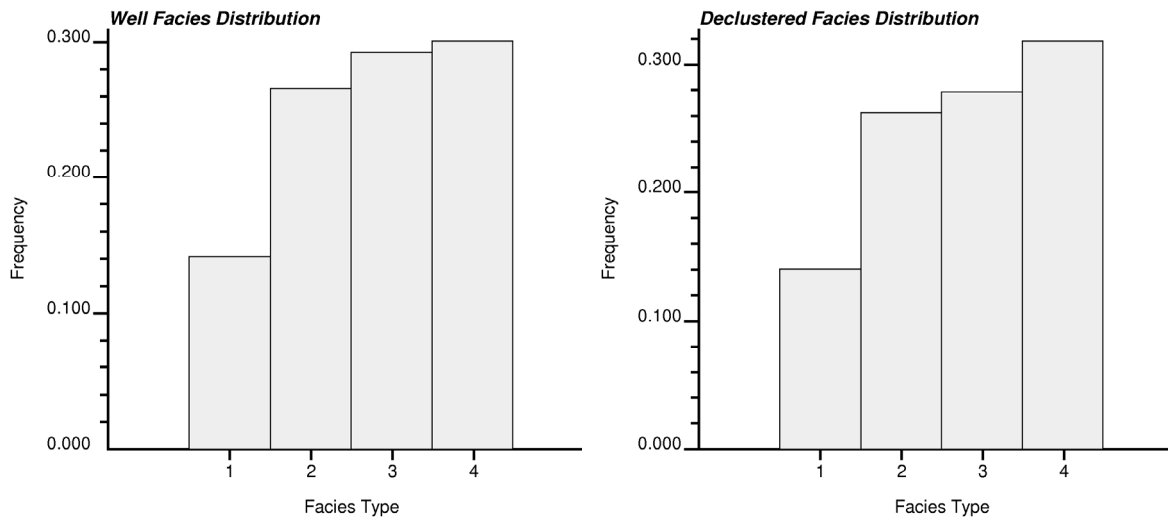
Figure 5-5 Histograms of facies type variable. The four facies, thick sand, thin sand, siltstone and mudstone are equal to 1, 2, 3 and 4, respectively.
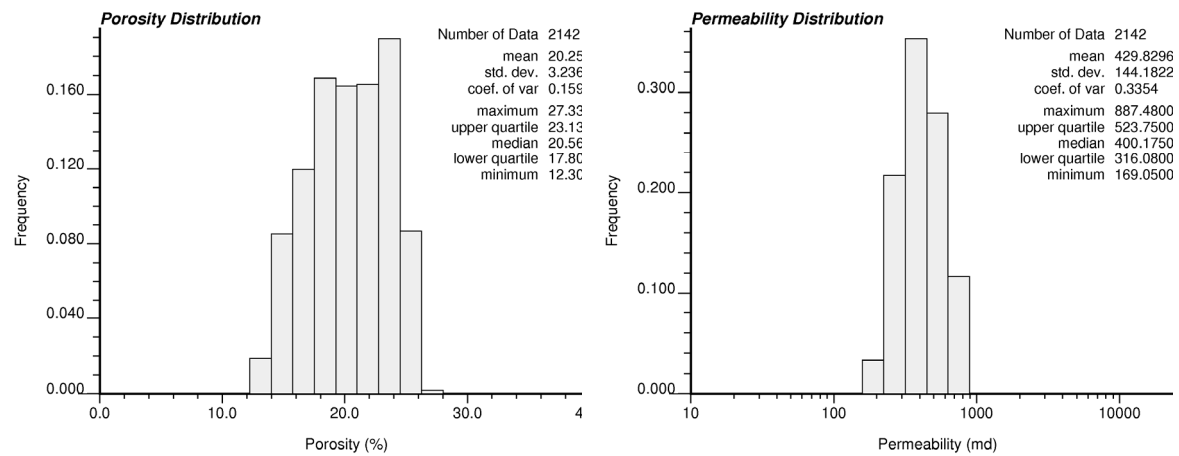
Figure 5-6 The distribution of porosity and permeability from synthetic well logs.
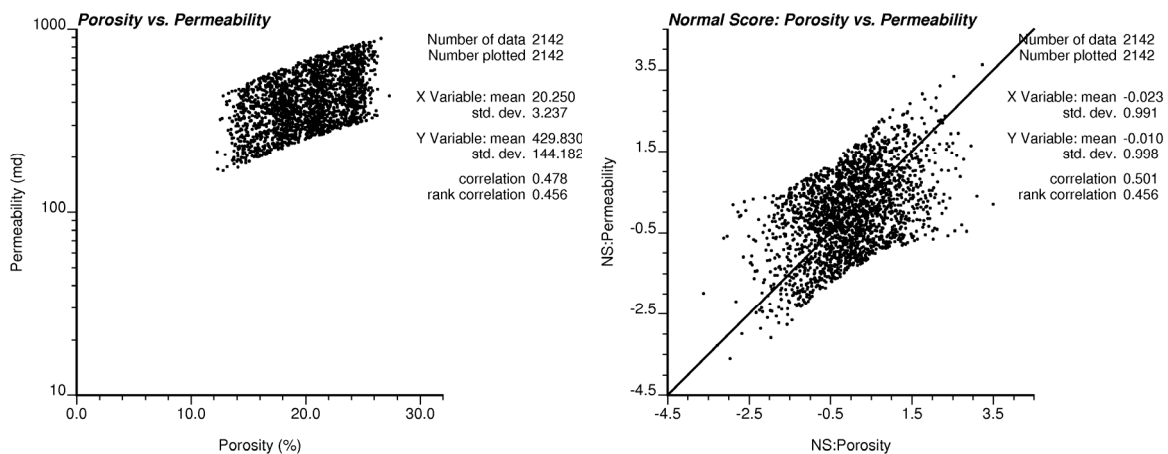
Figure 5-7 The scatter plots of well permeability and porosity before and after Gaussian transform.

5.2 Geostatistical Work Flow

A common geostatistical workflow for surface based modeling is to model: (1) reservoir geometry that honours available wells picks based on geological concept models and related statistical information; cell-based facies proportions model will be built at the same time based on modeled surfaces distribution; (2) lithofacies considering facies proportions model as secondary data; (3) porosity distribution within each facies; and (4) permeability distribution within each facies considering porosity as a secondary variable (Deutsch, 2002; Pyrcz, 2004). These models are conditioned to all available well data and analog information. Figure 5-8 illustrates the geostatistical workflow of surface-based modeling.

5.2.1 Model of Reservoir Geometry

Large-scale reservoir geometry can be visualized with seismic and are known for subsequent surfaces modeling. In this case study, two source locations for the turbidite lobes are based on global base surface geometry are selected. There are four facies types: graded sandstone, laminated sandstone, siltstone and mudstone (Table 5-1). Mudstone has the largest proportion (Figure 5-5). Subsequent flow event deposits have persistent internal lithofacies trends which are defined by a linear proximal-distal facies trend template (Figure 5-4). An idealized areal facies distribution is assumed.

Surface picks were automatic identified on porosity curves. As a curve identification approach, only shape information is used. Porosity is a function of lithology (shale content), diagenesis, epigenesist, and also other influence. The identified sandstone boundaries are good starting point for further analysis. Experienced geologists may adjust the results based on their geological understanding and by integrating other information that cannot be easily quantified, such as fine-scale depositional structures from core images. Figure 5-9 illustrates the automatic surface picks identification results of Well 13. The synthetic porosity curve has many short-scale fluctuations, but it is usually very smooth in practice if it is interpreted with well logs.

25 conditional surface models were built to demonstrate the surface based modeling approach. Although all conditional surface models honour available well picks, the number of surfaces and spatial structures are different, which indicates that the fine-scale reservoir structure has significant uncertainty. The number of surfaces is a good indicator of spatial structure uncertainty (Figure 5-10); it changes from 61 to 100 with a lognormal shape. The median number of surfaces is 78. Three conditional surface models are shown in Figure 5-11 to compare different spatial structures, which comprising 61, 79 and 100 flow events, respectively.

The surface models affect reservoir production performance. This is the initial motivation of quantitative stratigraphic forward modelling (Cross and Lessenger, 1998). Each realization of the reservoir structure is passed through the entire subsequent geostatistical reservoir characterization process.
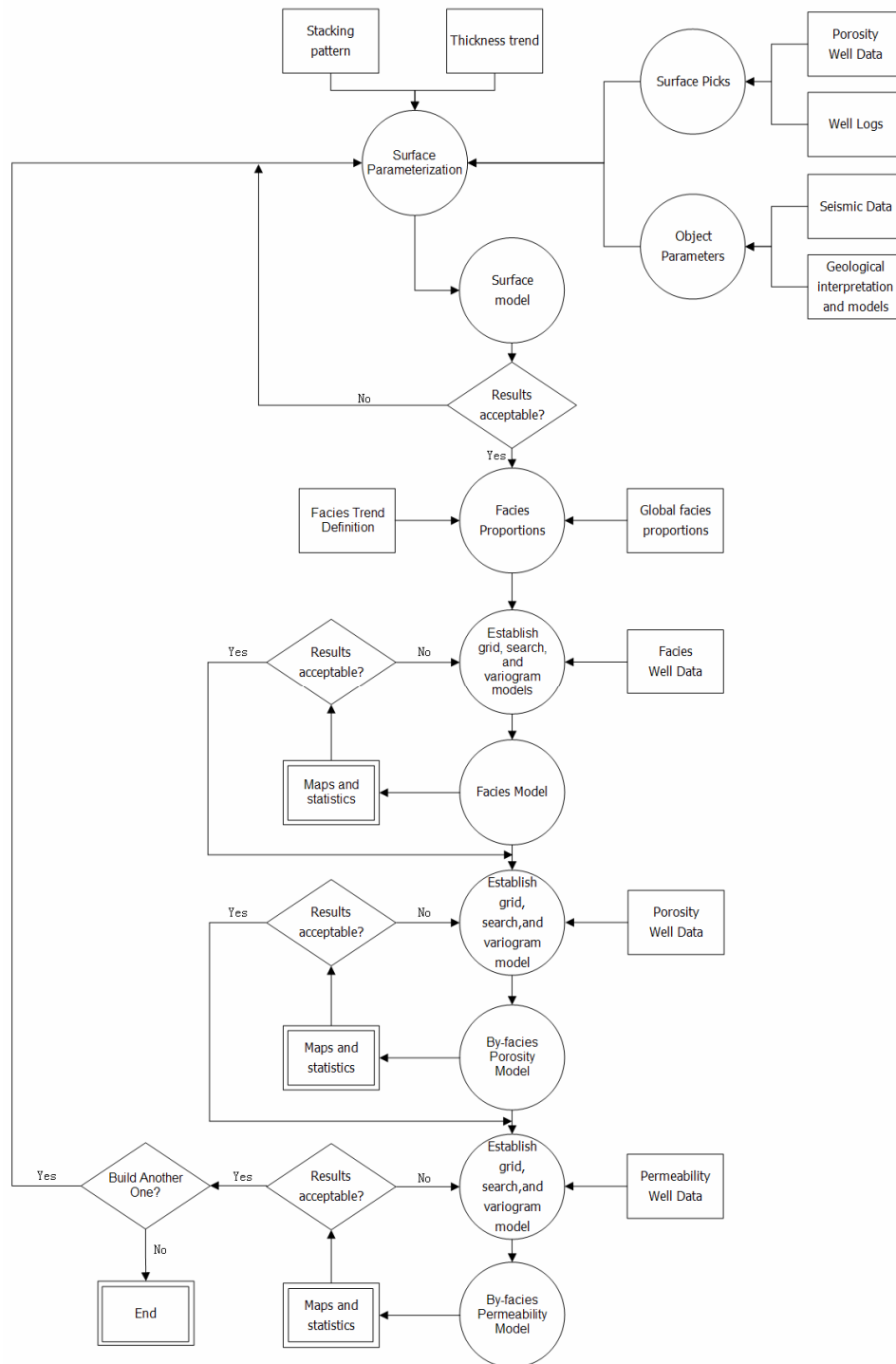
Figure 5-8 Geostatistical workflow of surface based modeling.
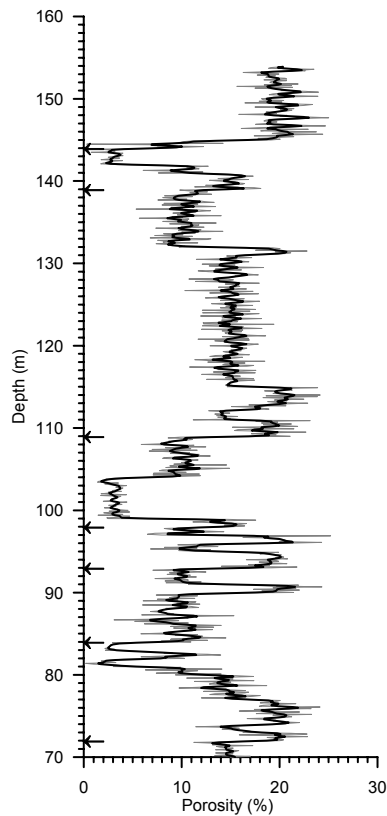
Figure 5-9 The auto surface picks identification results of Well 13. The gray curve is the original porosity curve. The dark curve is the moving window smoothed curve. The left arrows show the identified surface picks. The lowest surface pick was deleted during surface modeling due to the porosity continuity.
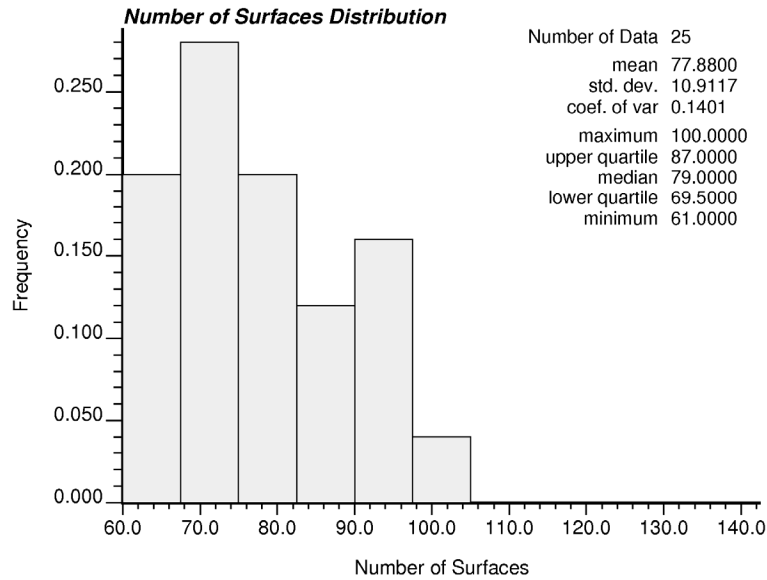
Figure 5-10: The number of surfaces distribution of the 25 conditional surface models.

(a)

(b)

(c)
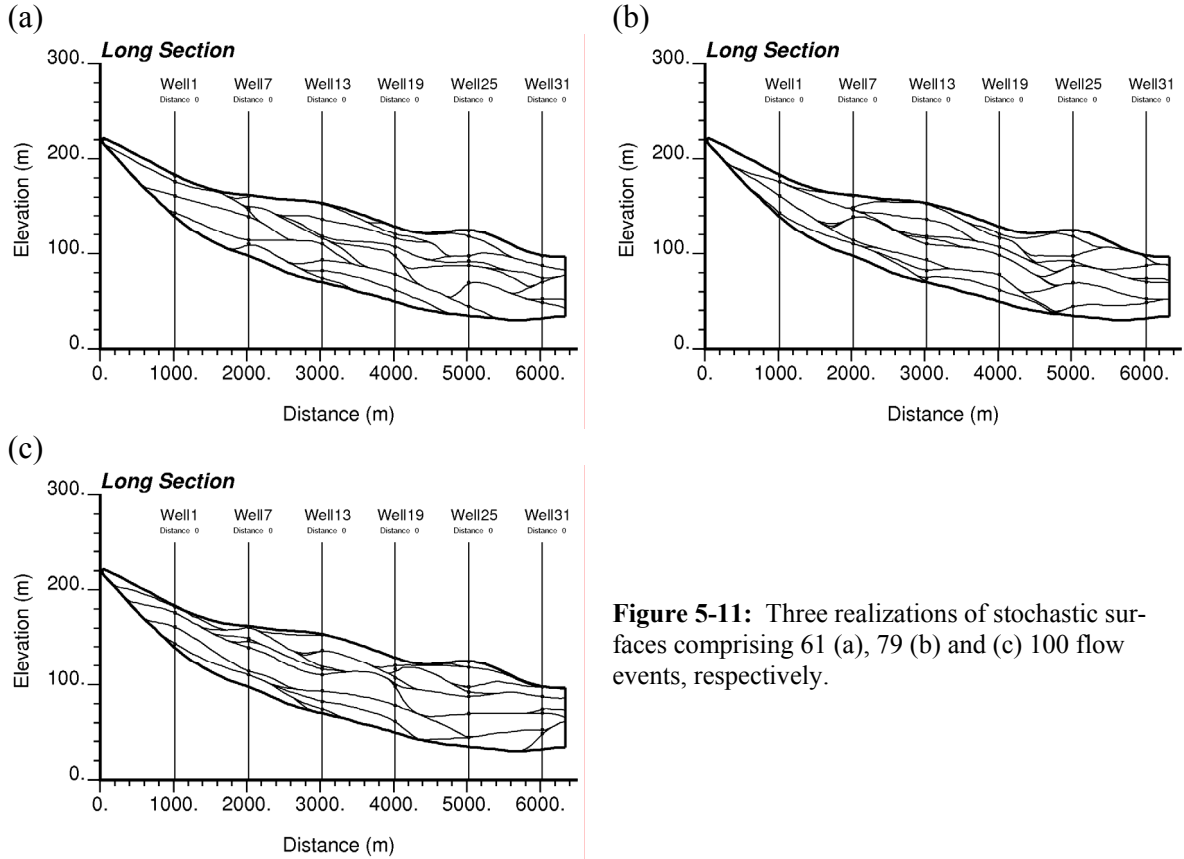
Figure 5-11: Three realizations of stochastic surfaces comprising 61 (a), 79 (b) and (c) 100 flow events, respectively.

5.2.2 Lithofacies Models

There are progressively finer sediments and thickening of the finer part of the sandstone / mudstone as the sediments go from proximal to distal direction. The trend information is integrated into cell-based facies model as facies proportions information. In Chapter 4, we have demonstrated the detail of facies proportions calculation methodologies. `BlockSIS` is applied in this case study.

The facies distribution inferred from log and core available at the wells are shown in Figure 5-6. The facies semivariograms are shown in Figure 5-12. The vertical variogram is well informed, but the horizontal variogram inference is a challenge for the continuity within each facies is much smaller than the average well distance. Three facies models comprising 61, 79 and 100 flow events are shown in Figure 5-13 to illustrate the surface-based facies modeling results.

Although both models honour available well data, the spatial distribution of facies changes from realization to realization. The distribution of facies is controlled by the reservoir structure. The distribution of facies will also affect reservoir production performance. Uncertainty of each realization of the facies passes through the entire geostatistical reservoir characterization procedure by controlling the reservoir petrophysical properties distributions. The combined contribu-

tion of structural uncertainty and facies distribution uncertainty to production uncertainty can be quantified in terms of production performance.

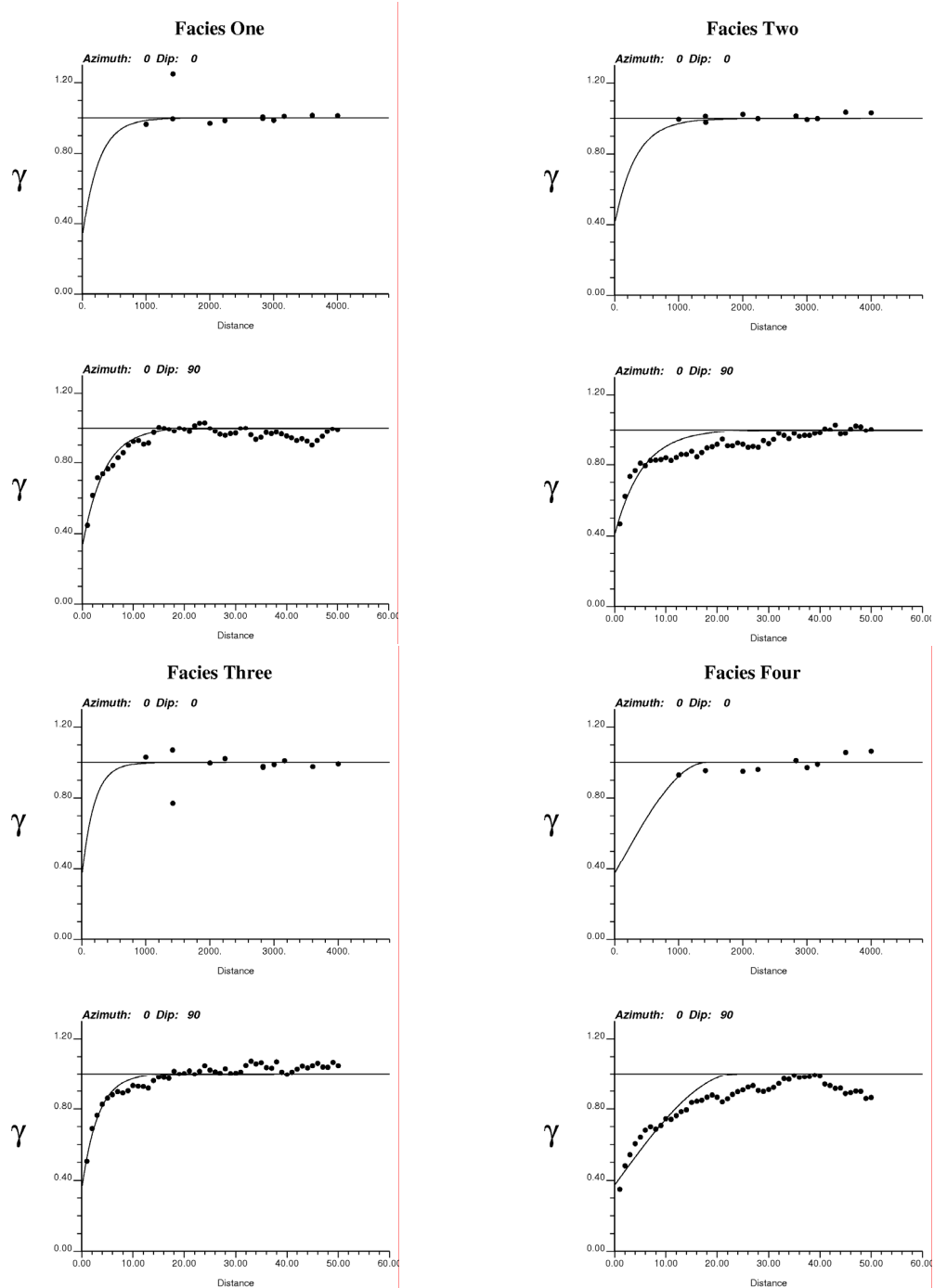**Figure 5-12:** Horizontal and vertical semivariograms of different facies.
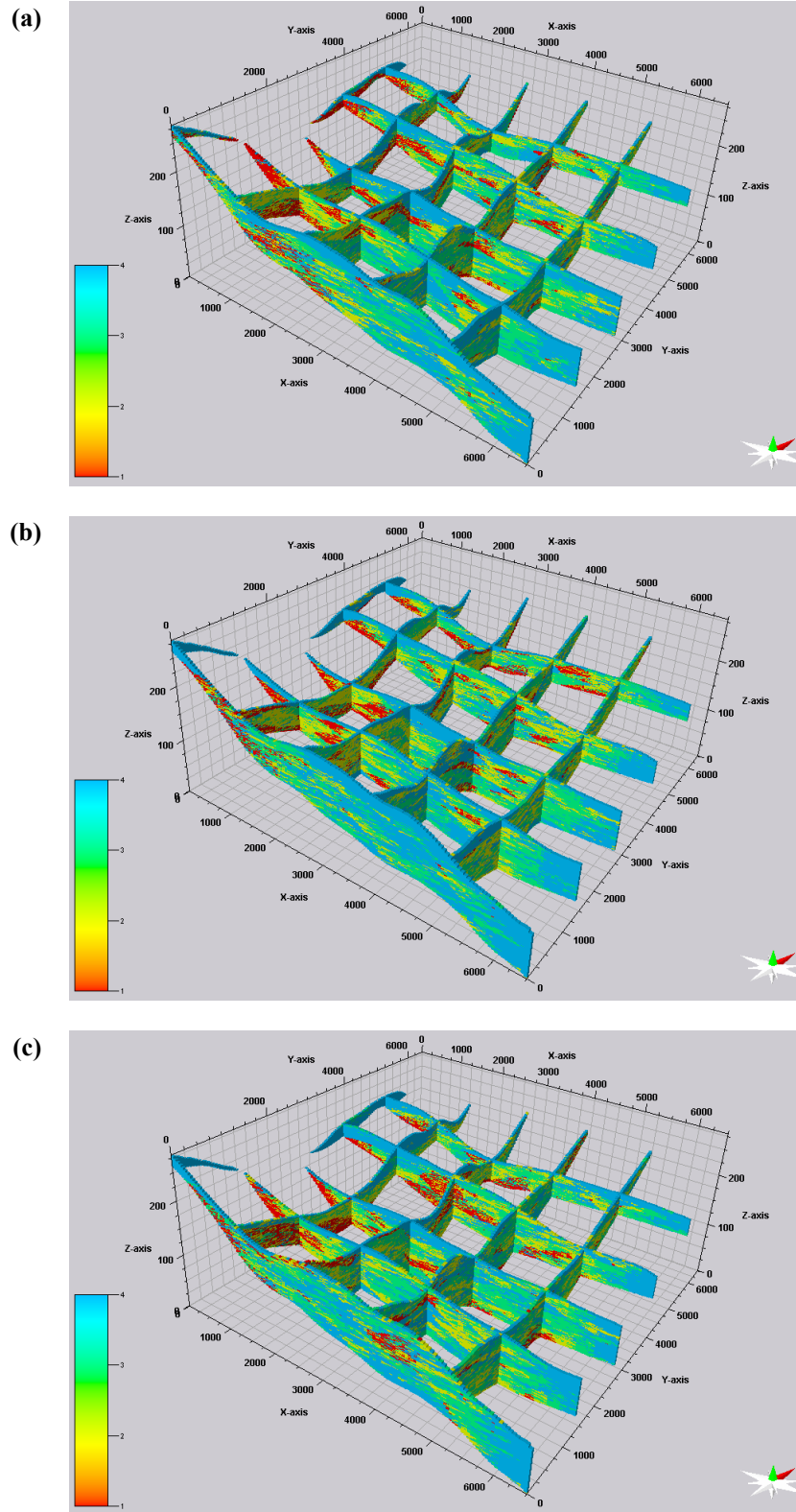
Figure 5-13: Fence diagrams of three facies models comprising 61 (a), 79 (b) and 100 (c) flow events, respectively.

5.2.3 Petrophysical Properties

Porosity and permeability are continuous variables within each facies. Porosity is simulated independently for each facies type. The results are merged using the facies model. Then permeability is simulated with the corresponding porosity realization as second variable for collocated cokriging on the by-facies basis (Deutsch, 2002; Deutsch and Journel, 1998).

For geological uncertainty assessment purposes, each geological model consists of a single realization of all parameters; therefore, a single realization of porosity and permeability are modeled in associated with each reservoir structure model and facies model. A single geological realization is then defined by a surface (reservoir structure) model, a facies model, a porosity model and a permeability model. The approach is computationally efficient to quantify geological uncertainty (Deutsch, 2002; Pyrcz, 2004). 25 reservoir petrophysical models were built.

The same grid specification used for surface and facies modeling is used for porosity and permeability modeling. The same cells populated with simulated facies codes are populated with simulated properties values. Therefore, the reservoir properties are only simulated between bounding surfaces.

The porosity and permeability distribution inferred from log and core available at the wells are shown in Figure 5-6. The correlation coefficient between the Gaussian transform of porosity and permeability may be inferred from available conditioning data and it is used for permeability modeling with collocated cokriging (Figure 5-7). The experimental porosity and permeability semivariograms were calculated in the plane of the flow events and orthogonal to the flow events (Figure 5-14).

25 by-facies porosity and permeability models were constructed (Figure 5-15, Figure 5-16). The uncertainty in porosity and permeability, i.e. the fluctuation from realization to realization, makes the last contribution to geological uncertainty.

The realizations of reservoir petrophysical properties may be applied for reservoir production uncertainty assessment. The geological uncertainty will be transformed into production uncertainty with flow simulation. Each geological realization is passed into the flow simulator to get a realization of reservoir production performance.

5.3 Some Comments

Adequate horizontal and vertical discretization is required to capture geological details. Facies and reservoir properties are often cell-based; therefore finer grid definition is needed to capture geological details and variability, especially along the transition zones of flow events. On the other hand, fine grid definition will create huge simulation grids that need significant professional

time on facies and reservoir properties simulation. In this case study, a 50m×50m×1m grid was applied and the major depositional characteristics were well captured.

The proposed surface conditioning approach works efficiently with a large amount of wells. The convergence procedure may be slow if the well density is very high.

The by-facies reservoir petrophysical properties semivariogram inference may be a big challenge in practice. In this case study, it is a serious problem even the well distance is only 1000 m.

5.4 Summary

A workflow for surface-based simulation is proposed with a synthetic example in this chapter. The workflow is proposed for reservoir geological uncertainty assessment, so each geological realization compromises a surface model, a facies model, a porosity model and a permeability model. The uncertainty in each step will be brought into next simulation stage and the entire geological uncertainty will be brought into reservoir production uncertainty.

With available surface picks, the surface models have great uncertainty. The number of flow events changes in a broad range. The reservoir properties models reflect the structural uncertainty by honouring facies distribution.

The proposed methodology works very well with relative dense well pattern. The reservoir structural model will control the later facies and reservoir petrophysical properties distribution. The proposed methodology may be applied to other fan-shaped depositional systems, such as small-scale delta fan. The default assumption is that the facies trend is understood.

The proposed methodology can be easily modified for more complicated geological settings. For example, streamlines may be modeled based on local bathymetry. The starting point of a flow event should be located on a streamline, instead of by random drawing.
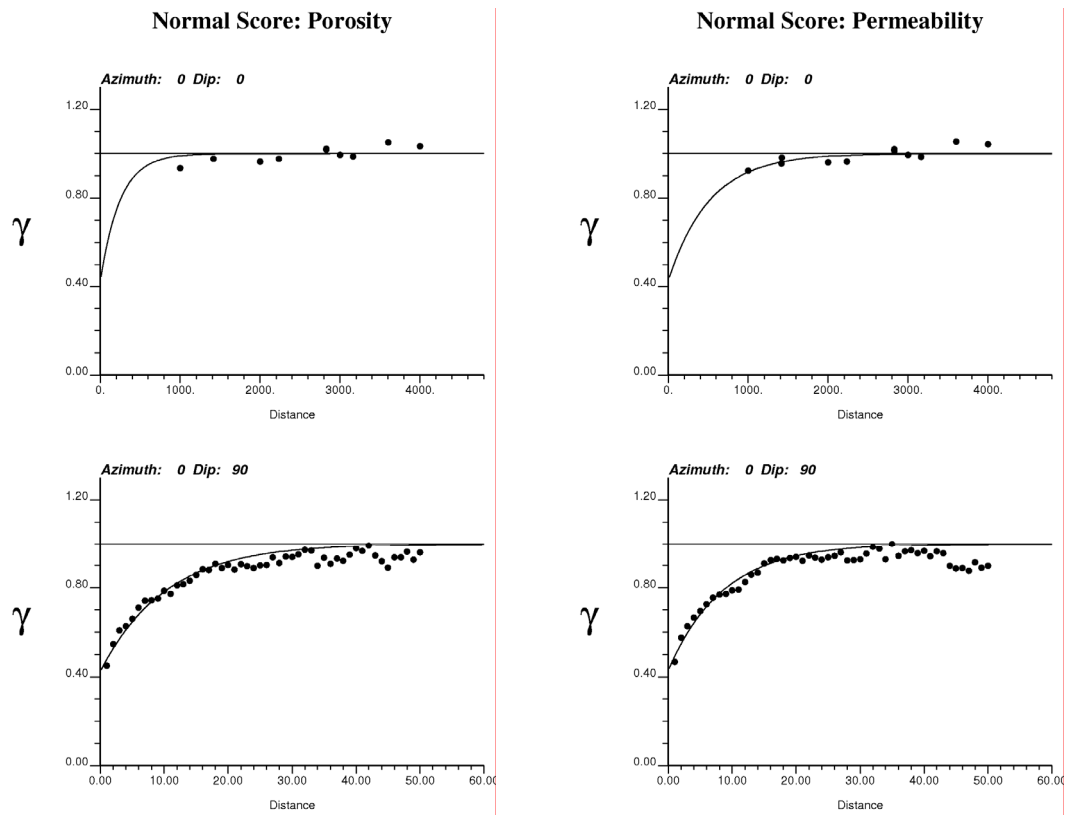
Figure 5-14: Horizontal and vertical semivariograms of the Gaussian transform of the porosity and permeability data.
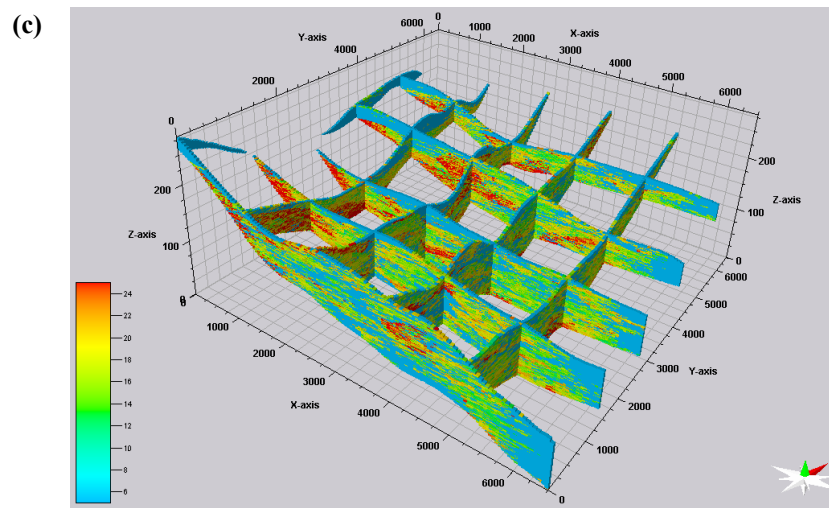
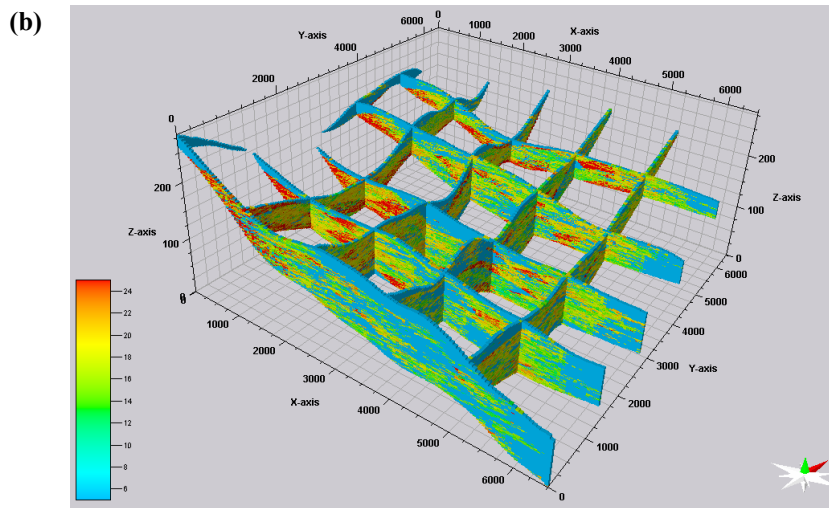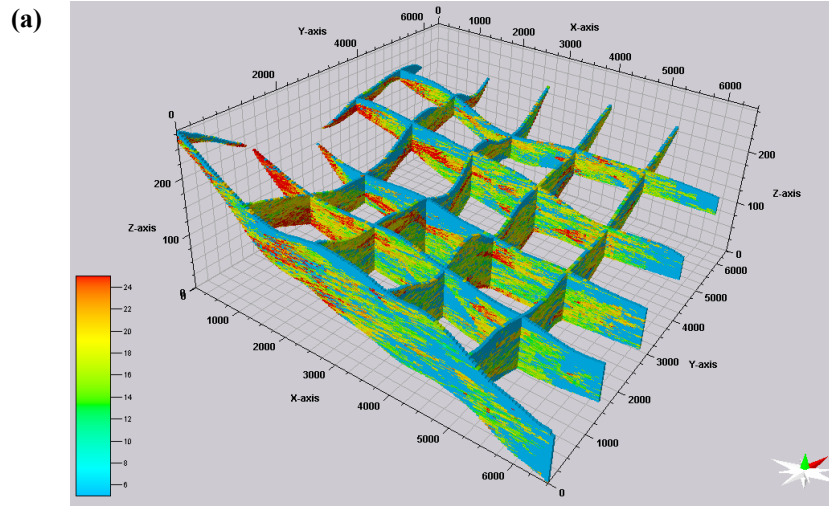**Figure 5-15:** Fence diagrams of three porosity models comprising 61 (a), 79 (b) and 100 (c) flow events, respectively.
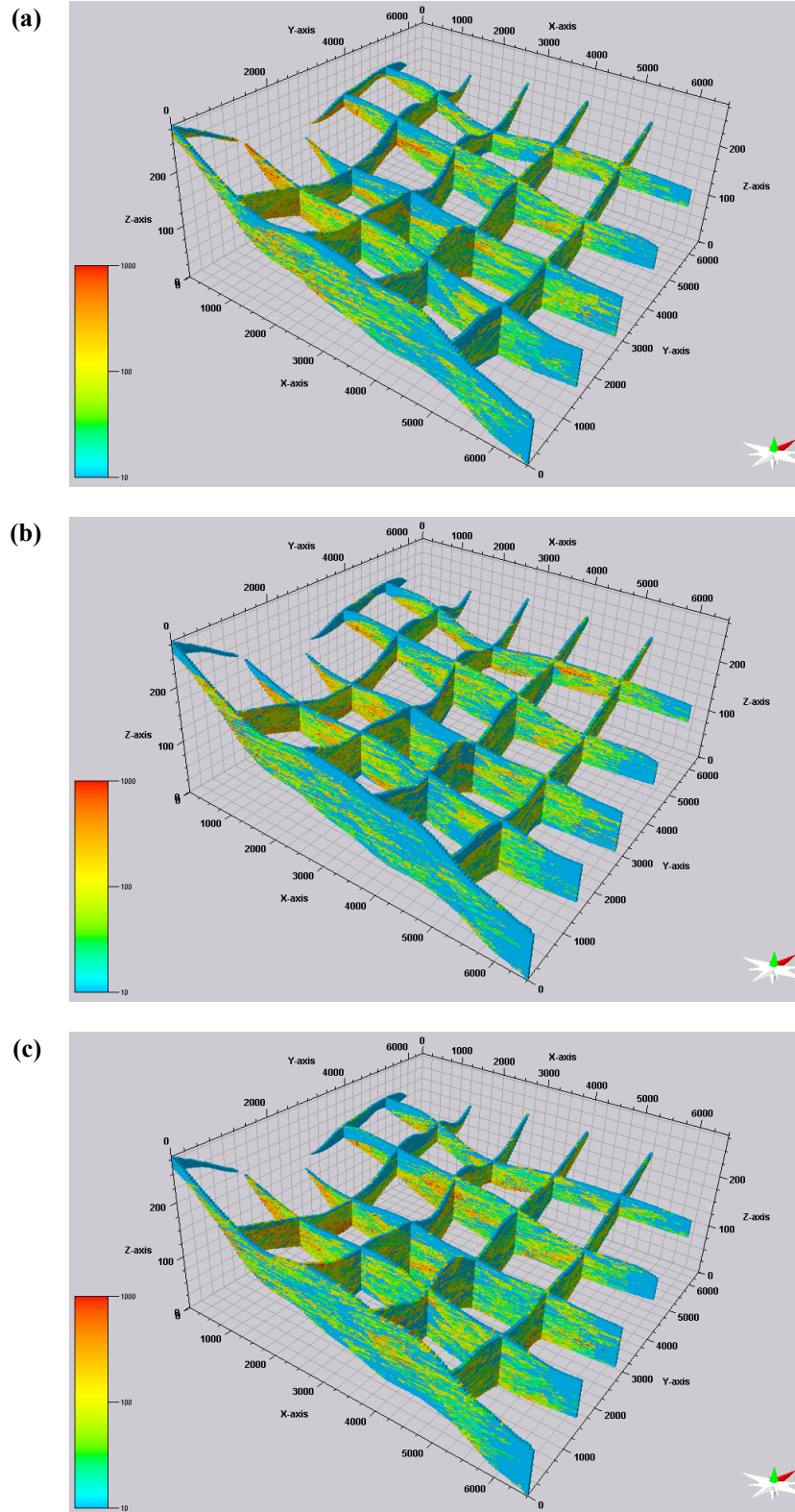
Figure 5-16: Fence diagrams of three permeability models comprising 61 (a), 79 (b) and 100 (c) flow events, respectively.

Chapter 6

Concluding Remarks

Stochastic surface modeling is applied in this research to capture complicated deepwater turbidite reservoir structures that has been a historic limitation of conventional geostatistical simulation approaches. The spatial structures of deepwater turbidite are complicated with clear curvilinear shapes. Conventional geostatistical simulation approaches focus on reproducing one- and two-point statistics only; therefore, they do not work well for these deepwater depositional systems. There are usually too few wells to control the spatial distribution of reservoir properties over the study area due to the high drilling costs in deepwater environments. This makes deepwater turbidite reservoir uncertainty assessment more difficult. The unique flow mechanism of such depositional systems results in lobes with similar spatial structures; therefore, modeling the lobe topography shapes becomes possible with the development of surface-based modeling techniques.

6.1 Summary

This research aims at developing a lobe event modeling program improving on former research. The original contributions made in this thesis include: (1) the base level concept from sequence stratigraphy is introduced into stochastic surface modeling to guide for surface positioning; (2) improved surface conditioning method for efficiently honoring large amount of wells; (3) stochastic stacking patterns reproduction; and (4) surface-based facies proportions calculation methodologies to integrate both geological concept model and areal and vertical trends.

1. Equilibrium profile

Equilibrium profile is an important concept in sequence stratigraphy analysis. There are lots of papers discussing large-scale equilibrium profile shapes in various depositional environments, such as beach, continental slope and fluvial environments. For small-scale turbidite lobe events modeling, it is impossible to build equilibrium profiles analytically. A local base level is assumed based on depositional mechanism analysis and applied in this research.

2. Improved surface conditioning method

The improved surface conditioning method is based on the rejection algorithm developed by Pyrcz (2004). To accelerate the optimized surface searching, a larger candidate surface is drawn with all available well picks located within it. Then the surface is adjusted to an optimized posi-

tion. To avoid introducing short-scale fluctuation, a dual-spline error surface fitting method is applied to model the error surface.

3. Honor stacking patterns

Stacking pattern has strong influence on connectivity and flow production. When transforming base surface to paraboloid or incline, the global surface gradient information is kept. This information is utilized in constructing surface probability distribution. Controlling the probability distribution allows common stacking patterns to be reproduced, including aggradation, progradation and retrogradation.

4. Surface based facies modeling

Surface models cannot be used directly in conventional cell-based facies simulation. Surface information has to be transformed to related information that can be integrated by cell-based simulation approach. The relative position information is transformed to facies proportions that can be integrated by conventional SIS-based facies modeling approaches. Both concept facies model and vertical and areal trends may be integrated. The spatial structure uncertainty is brought into facies modeling stage.

6.2 Future Work

Complicated depositional environments and flow mechanisms make it impossible to design a universal lobe events modeling program. There are some limitations for the current `LE_model` program that need to be addressed in future research.

1. Streamline construction

No streamlines are explicitly constructed in `LE_model`. The geometry is constructed based on the center line of a lobe. As a gravity driven turbidity current flow, local geometry strongly controls streamlines distribution and entry point location. It is also the major controlling factor of lobe orientation. The simulated streamlines could also honor the recognized streamlines on high-resolution seismic image.

2. Honor incomplete surface information

Small-scale surface can not be continuously traced on seismic image, but part of the surface may be visualized clearly on seismic. The incomplete surface information and recognized surface contacts have to be honored.

3. Conditional modeling depositional erosion events

Local depositional erosion events due to the strong destruction ability of turbidite current happen often in geological history. Therefore, the idealized spatial structures seldom exist. Erosion simulation is important on reproducing complicated reservoir structures. The proposed method can only work unconditionally at present.

4. Honor 3D facies trend directly

3D facies trend may be recognized on seismic. At present, only 1D and 2D facies trends information can be integrated using specified trend template.

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