Petroleum and Coal

Using satellite images to create training images for Multiple-point statistics modelling of meandering fluvial reservoirs

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Abstract

Geostatistical simulation using multiple-point statistics (MPS) has improved the quality and efficiency of reservoir models by replacing the conventional two-point statistics with multi-point statistics acquired from training images. As a stochastic method, multiple-point statistics requires the training image to satisfy the conditions of stationarity and ergodicity in order to capture patterns from the training image and reproduce them in the reservoir model. This limits the sources of analogue data that can be directly used to create geologically realistic training images. In this paper, I present a workflow for creating training images of meandering fluvial reservoirs from satellite images using the object-based and interactive facies modelling techniques and show that satellite images of modern fluvial depositional environments can serve as a library of analogues for meandering fluvial reservoirs. The workflow describes a simple process of creating stationary training images, which are geologically realistic directly from satellite images. This allows multiple-point statistics to capture the patterns contained in the training images. The extracted patterns, which serve as the main input for simulation of reservoir models, are reproduced in the resulting model.

Keywords: *Satellite images; training images; multiple-point statistics; meandering; fluvial; reservoirs.*

1. Introduction

Fluvial reservoirs are formed by sedimentary bodies with random, curvilinear geometries such as sinuous sand channels, levees, crevasse splays etc. Such random, complex shapes are poorly reproduced in geostatistical reservoir models using conventional two-point (variogram) statistics [1-4]. This limitation is due to the inability of two-point statistics correlation to adequately capture the irregular pattern and continuity of the facies bodies thus, reservoir connectivity and heterogeneity is often misrepresented. This pixel-based approach however, allows for effective data conditioning. In contrast, object-based modeling provides better and more realistic reproduction of random, curvilinear and highly connected facies geometries but data conditioning, especially with dense data constraints, of the resulting geostatistical model presents a great challenge and is the major limitation of this technique [2,5]. The strengths of these two techniques are combined in the multiple-point statistics (MPS) geostatistical reservoir modelling approach. By combining and utilizing these strengths, MPS is able to reproduce random and complex shapes while also honoring conditioning data.

Multiple-point statistics considers more than two points at a time and builds the model one pixel at a time [3]. It acquires statistics from quantitative, pixel-based, conceptual geological models known as training images [5]. The patterns contained in the training image are extracted and utilized to capture facies geometries and relationships, which are then reproduced during the stochastic simulations.

Training images are preliminary and fundamental requirements for MPS modelling. They describe and quantify spatial facies distribution, facies connectivity, lateral continuity, vertical

stacking pattern etc. They can be constructed based on hand-drawn conceptual models, outcrop mapping or stochastic algorithms and generated using unconditional object-based approach.

Satellite images can serve as a library of analogue data that can be used to generate training images for MPS. High-resolution satellite images of modern fluvial depositional environments capture the facies patterns and geometries expected in meandering fluvial reservoirs. This information is critical for modelling reservoirs and can be imported into MPS reservoir models via training images. Suitable sections of the satellite images can be meticulously selected and directly used to create training images.

2. Meandering fluvial systems

Fluvial environments are characteristically made up of channels and the overbank area. When rivers flow at either low flow stage or high flow stage, they are normally confined to the channels. At low flow stage, the level of water in the channel is far below the level of the channel banks, while at high flow stage, the channel is filled up to the channel banks or close to it. At other times however, the volume of water discharged could be too much for the channel to contain, resulting in flooding over the channel banks and onto the overbank area. For this reason, the overbank area is also known as the floodplain.

Coarser sediments are transported along the channels as bed load, while finer sediments are transported in suspension. The sediments are transported for as long as the energy of the flow is enough to carry them along. As the energy of the flow decreases, coarser sediments are deposited within the channels, while finer sediments subsequently settle out of suspension. During flooding, the sediment – bearing water flows onto the floodplain where the finer sediments settle out of suspension.

In areas of low gradient away from the upland source area (middle to lower parts of the fluvial system), the flow becomes sinuous resulting in the development of the meandering channel pattern. During flooding, suspended sediments carried in water spilled over the channel banks quickly settle out along the banks of the channel where they accumulate to form levees. When there is a rise in water level, the levees are often breached, resulting in the deposition of sediments in a 'fan-shaped' pattern spreading outward from the outer channel meanders to form crevasse splay. As water flows in a sinuous pattern, the outer banks of the channel are eroded and the sediments are deposited along the inner banks, forming point bars and causing the channel to continuously migrate laterally just as the point bar sequence accretes laterally. Over time, the channel meanders become larger and separated by narrow necks, which may eventually be breached, cutting off the meander to form oxbow lakes.

3. Training image

Training images are quantitative and visually explicit conceptual models, showing reservoir facies geometries, patterns, distribution and relationships. They represent the geologist's prior knowledge and understanding of the reservoir. The training image provides a database of the full range of possible patterns and relationships that are believed to be present in the target reservoir [4], from which multipoint statistics are extracted for simulation. It is a conceptual model, which is not conditioned to any data [4,6].

Early advances in MPS simulation proposed the use of 2D digitized outcrop photographs or hand drawn sketches as training images [4,6]. Generating 3D training images by combining 2D information was found to rely on weak assumptions, and introduced errors and uncertainties into the training image [7-8]. Later developments led to the widespread use of object based modeling for generating training images [4]. The object based modeling approach is perhaps the most common and uncomplicated approach for creating 3D training images by generating unconditional realizations. Training images can be generated from several other tools such as outcrop analogues, sequence stratigraphic studies and process-based models [9].

MPS algorithms based on SNESIM require the training image to have similar and repetitive patterns for those patterns to be extracted and reproduced. This principle is referred to as

stationarity [2,10]. By implication, this principle limits the outcrop analogues, models and other tools that can be used to generate training images because many outcrops are made up of non-stationary features and therefore unsuitable for creating training images. Although reservoirs are themselves not entirely stationary, it is good practice to split them into small stationary sections and generate a different training image for each section [9]). Multiple training images may also be required where considerable uncertainty exists regarding facies geometry due to limited geological knowledge [11]. In such situations, multiple training images with variable parameters such as size and orientation of facies, connectivity and heterogeneity should be generated to represent different scenarios.

The size of the training image in relation to the size of the largest feature to be reproduced in the reservoir model is important with regards to ergodicity. Training images should be at least twice the size of the reservoir to be simulated in the direction of the largest continuity due to ergodic fluctuations [10]. These fluctuations, resulting from calculation of parameters from a finite domain, are larger across larger distances over which they are measured. Thus channels, which are usually the largest features in fluvial reservoirs, appear broken along their lengths if the training image is smaller or the same size as the model.

4. General workflow

The following workflow (Figure 1) shows a summary of simple steps to follow to directly use satellite images of modern fluvial depositional environments to create training images for MPS simulation of meandering fluvial reservoirs.
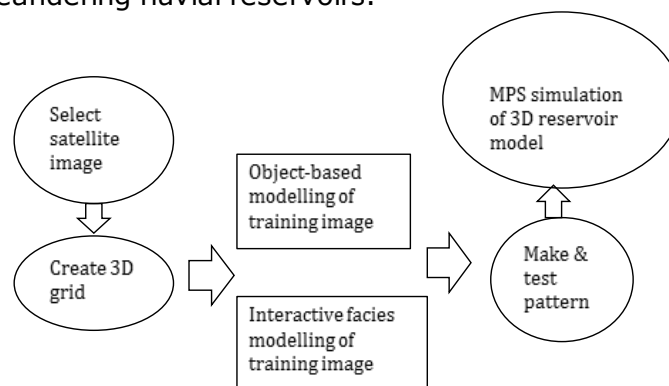

Figure 1. Workflow for using satellite images as analogues to model fluvial reservoirs
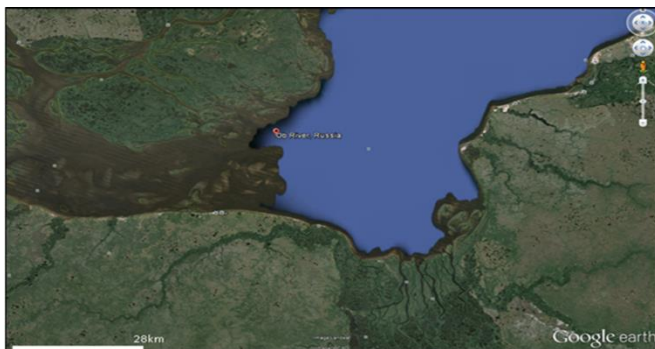
4.1. Satellite images

Google Earth provides high-resolution satellite images of modern fluvial depositional environments, for example the Ob River area, Russia (Figure 2). The area contains interesting patterns of meandering channels, which appear similar and repetitive. This is an important requirement for MPS to capture and reproduce the patterns from the training image.

Figure 2. Satellite image of the Ob River area, Russia (Google Earth)

Sections of the satellite image of this area can serve as modern analogues of meandering fluvial reservoirs to create training images. This ensures that the training images, although conceptual, are geologically realistic. The selected sections (Figure 3) show typical meandering channel patterns.

Figure 3. Satellite images of channel patterns in the Ob River area, Russia: (a) Meandering pattern with large meander loops, showing point bars (yellow circles), (b) Meandering pattern with smaller meanders (Google Earth)

4.2. 3D grid

The creation of training images involves creating an empty 3D grid on which the training image would be modeled. This is simplified in Petrel ® with the training image and pattern creator, which enables the user to create an empty, simple training image grid (TI grid) by defining the number of cells in the grid, as well as the cell size. The size of the grid may depend on the number, size or complexity of the objects to be populated, and has effects on the execution time. Therefore splitting the reservoir into smaller stationary sections will result in more, but faster training images.

4.3. Object-based training images

One of the most straightforward ways of creating 3D training images is by object-based modelling. This method produces geologically realistic geometries and relationships. Facies modelling under object-based modelling allows the user to select and define facies bodies in the training image (Figure 4). An unconditional training image containing user-defined objects can then be generated to mirror the facies in the satellite image.
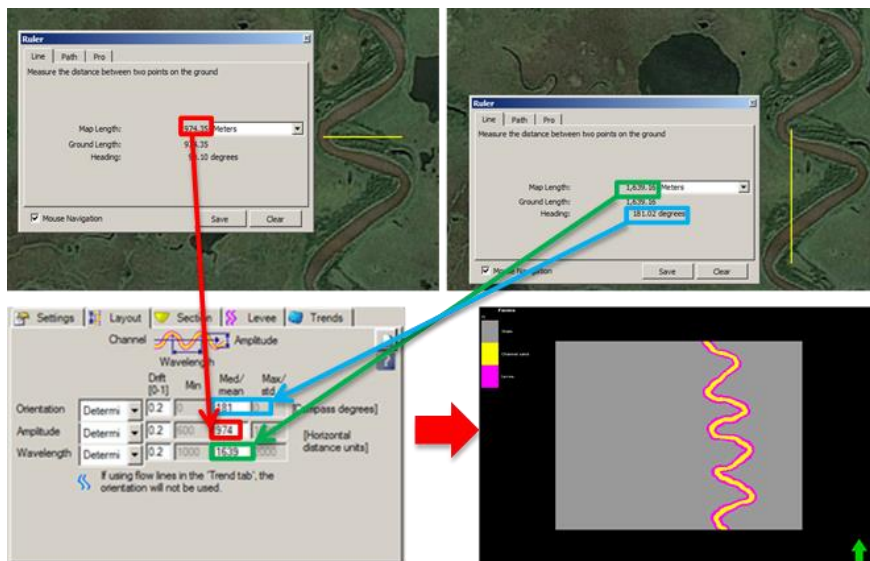

Figure 4. Inputting channel parameters into the object modeling process

The training image (Figure 5) was created using the channel object and associated levees facies bodies. The channel and levee dimensions such as orientation, amplitude, wavelength, width and thickness were defined. The default background facies is shale and so does not require the user to define any parameter for the floodplain.
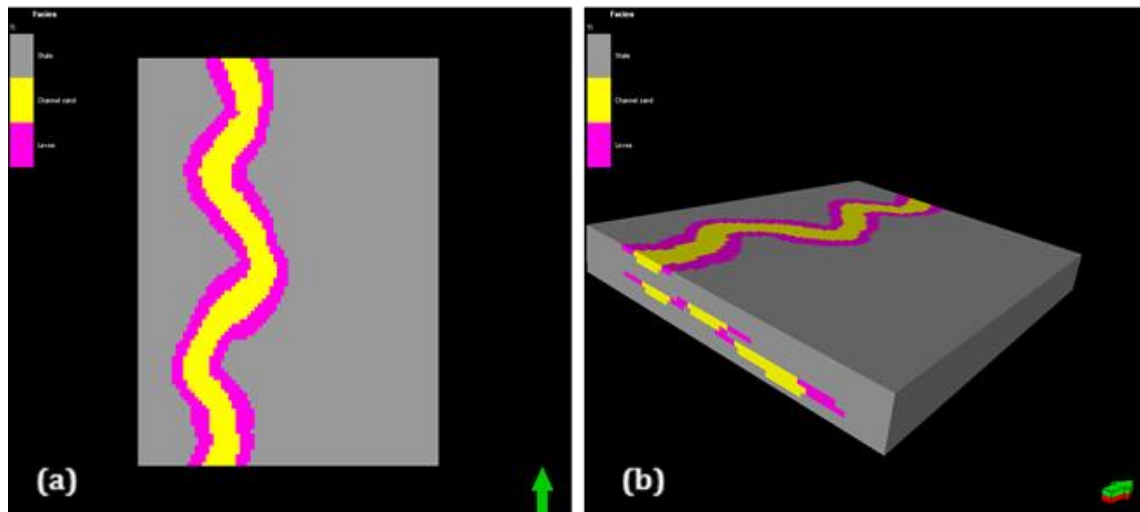

Figure 5. TI 1 – training image showing floodplain (grey), channel (yellow) and levee (pink): (a) map view, (b) oblique view
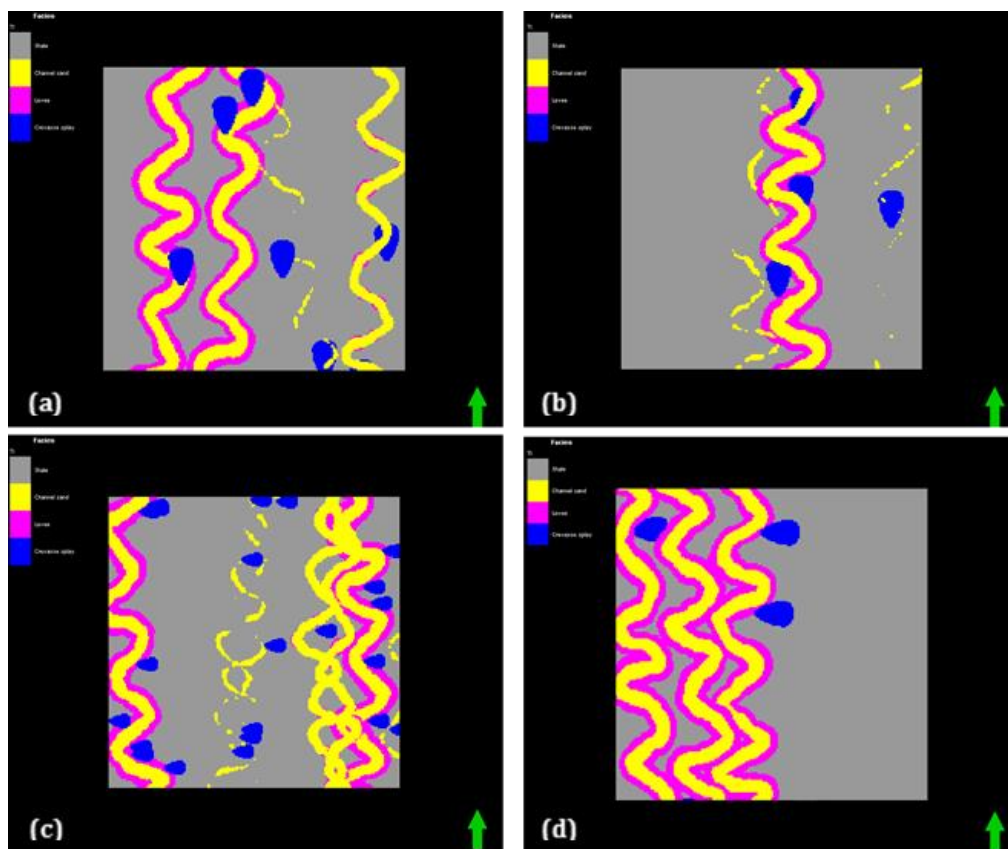

Figure 6. Stages of TI 2 creation process – training image (map view) showing floodplain (grey), channel (yellow), levee (pink) and crevasse splay (blue): (a) erosion rules not defined (b) erosion rules defined, but crevasse splay orientation not defined (c) crevasse splay orientation defined by directional trend property (d) crevasse splay constrained to the outer meanders by object curvature property

Crevasse splay, which form when levees are breached, typically spread outward from the outer meanders. Figure 6 demonstrates the process of creating this relationship. To model the relationship, the erosion rules must be defined for the crevasse splay to erode and overwrite the levees and the floodplain only. Without defining these rules, the crevasse splay are randomly populated in the training image, including within channels (Figure 6a). Defining the erosion rules does not only prevent this, but also attaches the crevasse splay to the levees (Figure 6b). At this stage, it is necessary to generate the directional trend property to define the orientation of the crevasse splay such that they spread outward from the channels (Figure 6c). Generating the object curvature property and using it as a volume probability property constrains the crevasse splays to the outer meanders which have the highest positive curvature values, giving a more geologically realistic relationship (Figure 6d).

The process of adding oxbow lake objects to the training image is similar to that of the crevasse splay. It involves defining the erosion rules for oxbow lake to erode and overwrite floodplain only, and generating the directional trend property to define the orientation of the oxbow lakes (Figure 7). Defining the erosion rules is important to prevent older deposits (oxbow lake) from eroding more recent deposits (channels).

Figure 7. TI 3 – training image (map view) showing floodplain (grey), channel (yellow), levee (pink), crevasse splay (blue) and oxbow lake (orange)

4.4. Interactive facies modelling training images

Interactive facies modeling involves direct painting of facies on the 3D grid. To make the grid visible, a constant value (0) was assigned to the TI grid using the property calculator, which populated the entire grid with background facies (shale). Once this is created, the user can paint the other facies on the TI grid using the facies paintbrush. The user can also filter through the layers of the 3D TI grid and paint the facies on the layers (Figures 8 and 9).
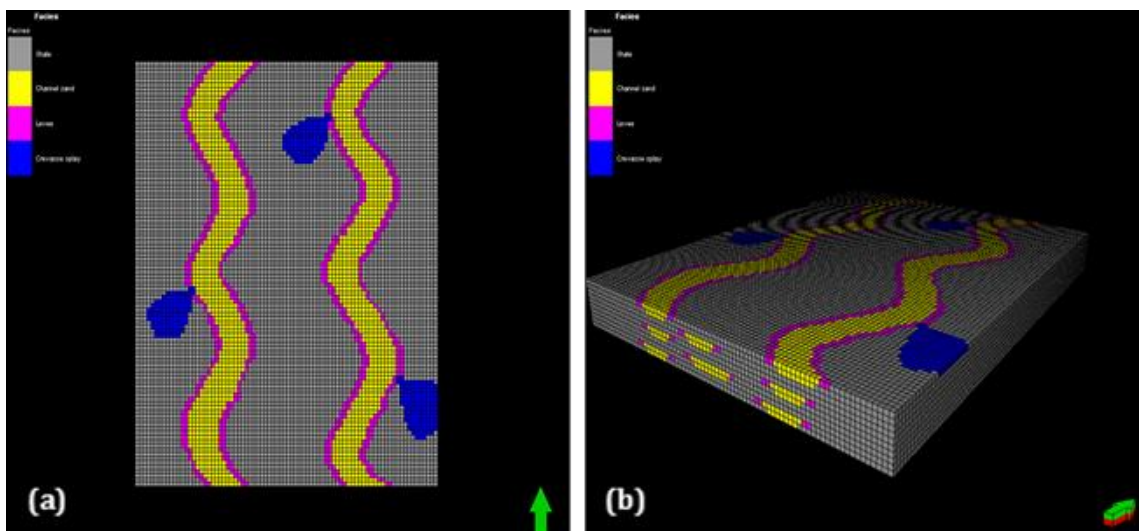

Figure 8. TI 4 – training image showing floodplain (grey), channel (yellow), levee (pink) and crevasse splay (blue): (a) map view, (b) oblique view
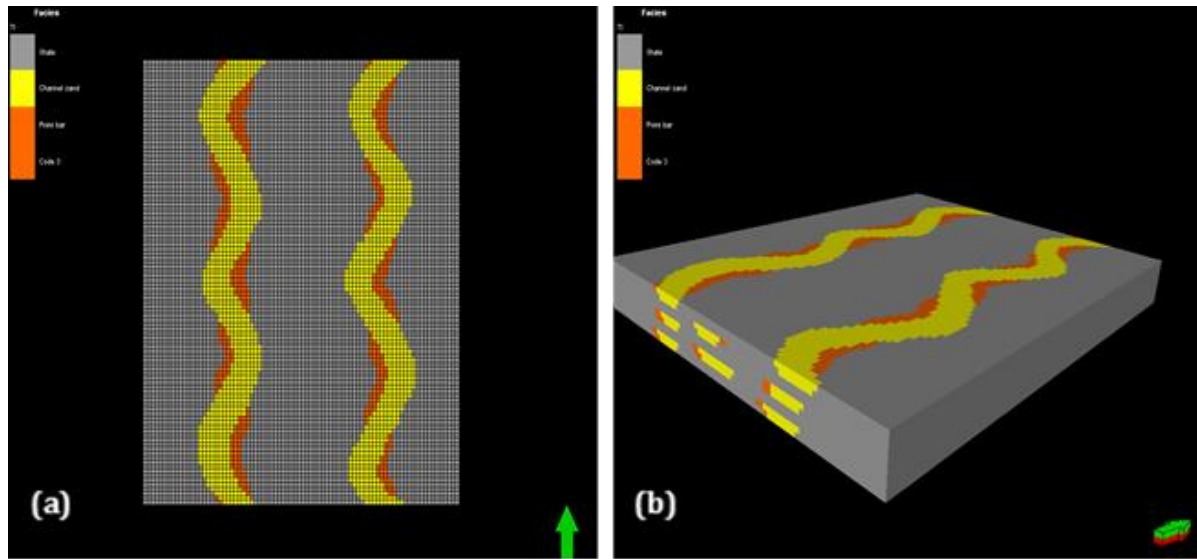
Figure 9. TI 5 – training image showing floodplain (grey), channel (yellow) and point bar (orange): (a) map view, (b) oblique view.

The interactive facies modelling technique also allows the user to directly trace the patterns on the satellite image onto the TI grid. Selected sections of satellite image can be imported into Petrel as bitmaps. Once imported, the limits of the bitmaps can be set to match the TI grid parameters (Figure 10a), so that the bitmap can fit onto the grid. The bitmap can be placed on the grid by setting its Z (depth) value to 0 (Figure 10b).
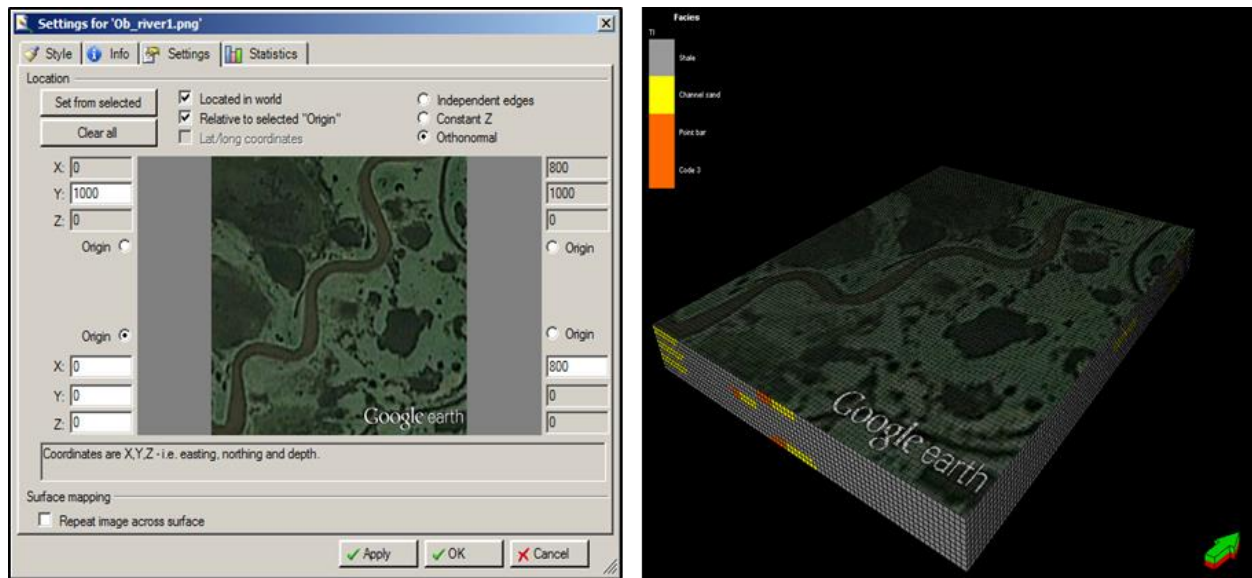

Figure 10. a. Limits of bitmap set to match TI grid parameters, b. Oblique view of bitmap placed on TI grid

The interactive facies modelling technique is especially suitable for patterns that cannot be modelled with the facies bodies available in object-based modelling, such as point bar and large meander loops with narrow necks (Figure 11). Such patterns are best created using interactive facies modelling.
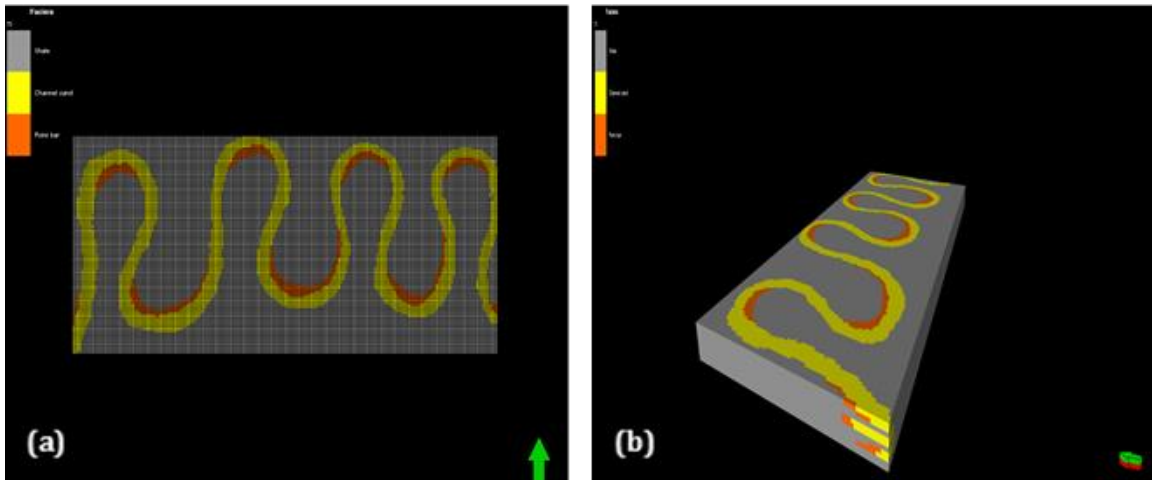
Figure 11. TI 6 – training image showing floodplain (grey), channel (yellow) and point bar (orange): (a) map view, (b) oblique view

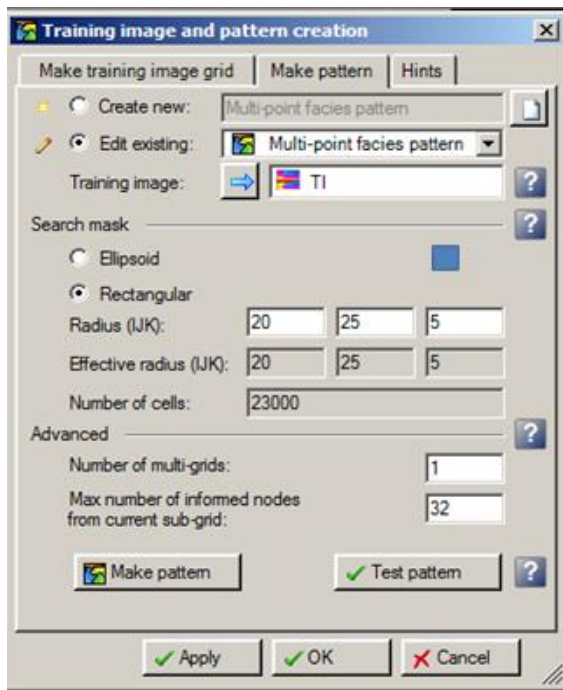## 4.5. Multi-point facies patterns

Figure 12. Training image and pattern creation dialog box

MPS utilizes patterns extracted from training images as its main input, which are reproduced during the stochastic simulation. Petrel ® allows the user to create these patterns (Figure 12), which explain the neighborhood relationship of facies. This makes the process more intuitive, as the user is able to visualize the patterns to be reproduced prior to simulation.

It is important to consider the effects of the search mask and multi-grids on the patterns (figure 12). During multi-point facies pattern creation, the coarsest grid is populated first. The coarsest grid is given by $2^{(m-1)}$, where 'm' is the number of multi-grids. For example, if 2 is chosen as the number of multi-grids, the coarsest grid will be $2^{(2-1)} = 2$. This means that the second cell in every direction would be populated first, starting with the central cells. For 4 multi-grids, the coarsest grid will be $2^{(4-1)}= 8$, which means that the 8th cell in every direction would be populated first. This implies that the smaller the number of multi grids, the better the patterns are reproduced, and the larger the search mask needed to cover the required area.

Figures 13 and 14 show the effect of ergodic fluctuations on the extracted patterns. The patterns appear broken in the direction of their largest continuity i.e. channels lengths (larger distance) as manifestations of this fluctuations. The extracted patterns (Figures 13 and 14) display these channel discontinuities because they are of the same size as the training images (Figures 5 and 9, respectively). This effect can be eliminated when building the reservoir model. To eliminate the effect, the training image size must be at least twice as large as the largest feature (channel length) reproduced in the reservoir model.
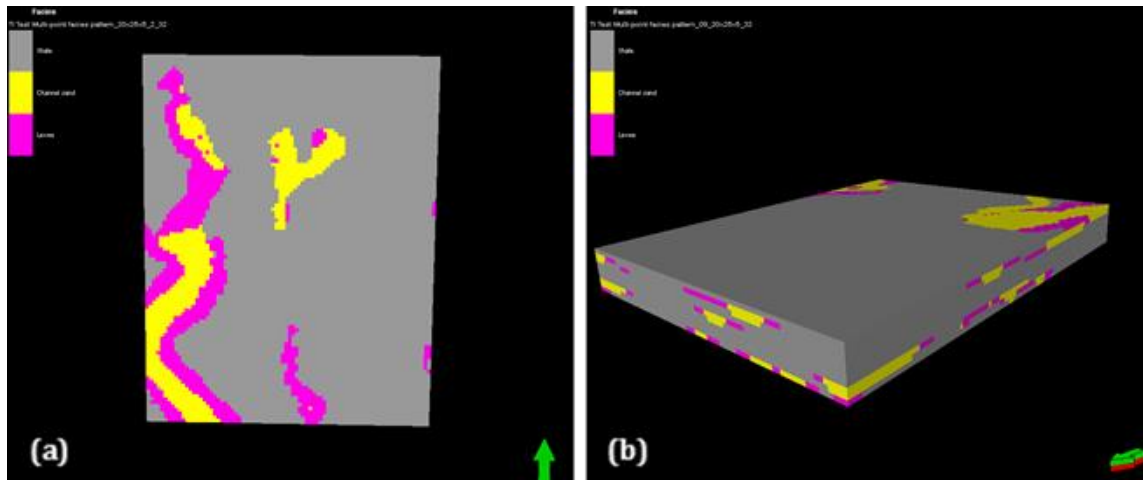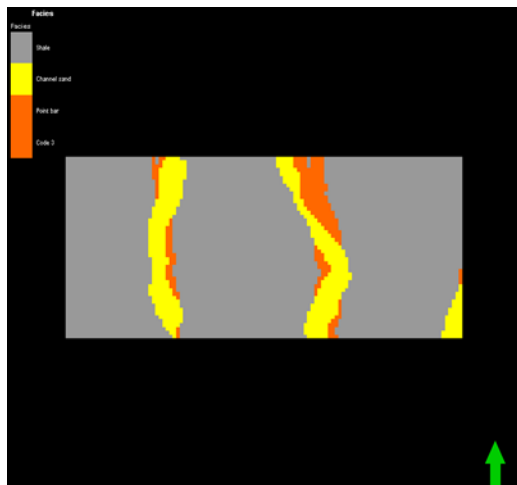
Figure 14. Multi-point facies pattern from TI 5 showing floodplain (grey), channel (yellow) and point bar (orange): (a) map view, (b) oblique view

4.6. MPS Model

The pattern (Figure 14) extracted from TI 5 (Figure 9) was used to create a simple unconditional conceptual MPS model. The model was built to half the size of the training image in the direction of the channels lengths to prevent the manifestation of ergodic fluctuations. The channels are the largest features to be reproduced in the reservoir model hence the smaller size in the direction of their lengths. The pattern was reproduced during the stochastic simulation and the resulting model (Figure 15) shows complete and continuous channels across the floodplain.

Figure 15. Map view of a simple conceptual MPS reservoir model showing floodplain (grey), channel (yellow) and pint bar (orange)

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5. Conclusions

Satellite images of modern fluvial depositional environments can serve as a library of analogues for meandering fluvial reservoirs, which can be used to create training images for multiple-point statistics. However, this goes with the caveat that they must be stationary. The principle of stationarity, which MPS relies upon to capture and reproduce the information contained in a training image, limits the analogues that can be used to create training images. Suitable satellite images, which satisfy the condition of stationarity can be directly used to create training images based on the object-based and/or the interactive facies modelling techniques following the workflow presented in this paper. The training image must be at least twice the size of the reservoir model in the direction of channels lengths to prevent the manifestation of ergodic fluctuations as channel discontinuities in the reservoir model.

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