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Simulation of heterogeneity in a point-bar/channel aquifer analogue

Simulazione dell'eterogeneità in un analogo di acquifero fluviale meandriforme (sistema barra puntiforme/canale)

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ABSTRACT - The aim of the study is the geostatistical simulation of fine-scale heterogeneities of a gravelly sand aquifer analogue from a quarry exposure in the Lambro River valley.

Three different simulation methods have been used and compared. The analogue consists of two superimposed bar-channel units of sand and subordinate gravel that formed in two different meander loops of the Roman-Medieval Lambro River. We developed an architectural hierarchical model based on the data obtained from direct inspection of 5 quarry exposures, that have been mapped and logged during excavation. In the analysed volume (approximately 30000 m^3) four operative hydrofacies have been recognised: very fine sand and silt; sand; gravelly sand; open framework gravel. Transition-probability and variographic analysis of the operative hydrofacies were computed both for the entire dataset and for the individual depositional elements, after discretization of the facies maps with square cells (spacing 0.05 m). This analysis was aimed to obtain the correlation length of each hydrofacies along different directions. The geostatistical simulations have been conditionated to: i) the discretized facies maps, ii) the measured logs and iii) the facies proportions. Several equiprobable realizations were computed for a test volume of approximately 400 m^3 and for the entire volume using three different simulation techniques: 1) Sequential Indicator Simulation (SISIM), 2) Transition Probability Geostatistics (T-ProGS) and 3) Multiple Point Simulation (MPS).

From the comparison of the different simulations, the following consideration can be pointed out: i) with every method the geological model is best reproduced when the simulations are realised separately for each highest rank depositional element and subsequently merged; ii) the three methods yield different images of the volume. In particular MPS is efficient in mapping the geometries of the most represented hydrofacies, whereas SISIM and T-ProGS can account for the distribution of the less represented facies.

KEY WORDS: aquifers, geostatistics, Multiple Point Simulation MPS, Sequential Indicator Simulation SISIM, T-ProGS.

RIASSUNTO - Viene presentato il risultato della simulazione geostatistica a piccola scala di un analogo di acquifero ghiaioso-sabbioso proveniente da un'esposizione in cava nella valle del Fiume Lambro. Sono stati impiegati tre differenti metodi di simulazione e cui risultati sono stato successivamente confrontati. L'analogo comprende due elementi deposizionali barra-canale sovrapposti, composti da sabbia con subordinata ghiaia e formati in due cicli evolutivi di età storica (Romano e Medioevale) del Fiume Lambro. È stato sviluppato un modello gerarchico basato sui dati ottenuti dall'osservazione di 5 fronti di cava, che sono stati cartografati e misurati durante lo scavo. Sono state calcolate le probabilità di transizione ed i variogrammi, sia sull'intera base di dati che sui singoli elementi deposizionali, dopo la discretizzazione delle mappe di facies con celle quadrate (lato 0.05 m). Questa analisi è stata effettuata pricipalmente per ottenere la distanza di correlazione di ogni idrofacies nelle diverse direzioni.

Il volume analizzato, di circa 30000 m^3 (47 m×75 m×8.6 m), è stato simulato distribuendo nello spazio 4 idrofacies operative (sabbia molto fine e limo, sabbia, sabbia ghiaiosa, ghiaia con struttura aperta). Le simulazioni sono state condizionate a: i) mappe di facies discretizzate, ii) sezioni stratigrafiche di dettaglio misurate, iii) proporzioni di facies. Sono state ottenute diverse simulazioni equiprobabili sia per un volume di prova di circa 400 m^3 che per l'intero volume. Sono state utilizzate tre differenti tecniche di simulazione: 1) simulazione sequenziale delle variabili indicatrici (SISIM), 2) simulazione con le probabilità di transizione (T-ProGS) e 3) simulazione multi-punto (MPS).

Dal confronto delle differenti simulazioni si evidenzia che: con qualunque metodo si ottengono risultati più realistici quando gli elementi deposizionali di più alto rango vengono

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simulati separatamente e quindi composti; i tre metodi utilizzati mostrano diversa efficacia nel riprodurre differenti caratteristiche del volume: MPS è più efficiente nel simulare le geometrie delle idrofacies più abbondanti, SISIM e T-ProGS forniscono risultati più soddisfacenti di MPS nella distribuzione delle facies meno rappresentate.

PAROLE CHIAVE: acquiferi, geostatistica, Multiple Point Simulation MPS, Sequential Indicator Simulation SISIM, T-ProGS.

1. - INTRODUCTION

The hydrogeological properties of alluvial sediments are determined by textural variations within the hierarchic arrangement of depositional units, from individual strata to depositional systems, and by the geometry of these units at different scales (JORDAN & PRIOR, 1992; LUNT *et alii*, 2004; BRIDGE & LUNT, 2006; RUBIN *et alii*, 2006). This complex heterogeneity, which is characterized by multiple scale lengths, affects groundwater flow and contaminant transport. Reliable flow and transport numerical models can be developed when this complexity is sufficiently well-known and eventually reproduced by geostatistical simulations. Because it is not always feasible to map the fine-scale heterogeneity in the subsurface (meters to sub-meters), several studies have been devoted to the analysis of outcropping reservoir/aquifer analogues as well as of modern analogues (LIU *et alii,* 1996; ANDERSON, 1997; HUGGENBERGER & AIGNER, 1999; HEINZ *et alii,* 2003; HEINZ & AIGNER, 2003; LUNT *et alii,* 2004, FELLETTI *et alii,* 2006). Exposed aquifer analogues allow to test the results of different simulation techniques at different scales.

Many geostatistical grid-based approaches are available for distributing facies heterogeneities through space. For a discussion about their applicability in practical situations see DE MARSILY *et alii* (2005) and FALIVENE *et alii* (2007). In this work lithofacies distribution was simulated using Sequential Indicator Simulation (SISIM; GOOVAERTS, 1997; DEUTSCH & JOURNEL, 1992), Transition-probability geostatistics (T-ProGS; CARLE & FOGG, 1996) and Multiple Point Simulation (MPS: STREBELLE, 2002, LIU *et alii,* 2005), which simulate the different facies in the form of coded indicator-type variables where each value corresponds to a given facies.

SISIM has been applied at different scales in a variety of depositional settings such as alluvial (JOURNEL *et alii*, 1998; SEIFERT & JENSEN, 1999; ZAPPA *et alii*, 2006; FELLETTI *et alii*, 2006; FALIVENE *et alii*, 2007), deltaic (CABELLO *et alii*, 2007), aeolian (SWEET *et alii*, 1996), and turbiditic (JOURNEL & GÓMEZ-HERNÁNDEZ, 1993; FALIVENE *et alii*, 2007).

T-ProGS has been used to model facies distribution in braided river deposits (FELLETTI *et alii*, 2006) and in alluvial fans (FOGG *et alii*, 1998; CARLE *et alii*, 1998; WEISSMANN *et alii*, 1999; WEISSMANN & FOGG, 1999).

MPS has been used to reconstruct turbiditic reservoirs using 3D training images and conditioning data from boreholes and geophysics (STREBELLE *et alii,* 2003) and to make 3D reconstructions starting from 2D training images at the pore scale (OKABE & BLUNT, 2004).

The results from the three above mentioned techniques of geostatistical simulation are compared with each other; the case study is an aquifer analogue, exposing two composite point bar-channel depositional elements of a meandering river depositional system.

1.1. - CASE HISTORY

Excavation of gravel and sand in the Po alluvial plain offers several ephemeral exposures of aquifer analogues of different fluvial types. For this study we had the opportunity to investigate the historical sediments of the Lambro River at a quarry site south of Milan (fig. 1). In this sector, the Lambro River is a meandering river, flowing since the post-glacial age within a narrow valley encased into

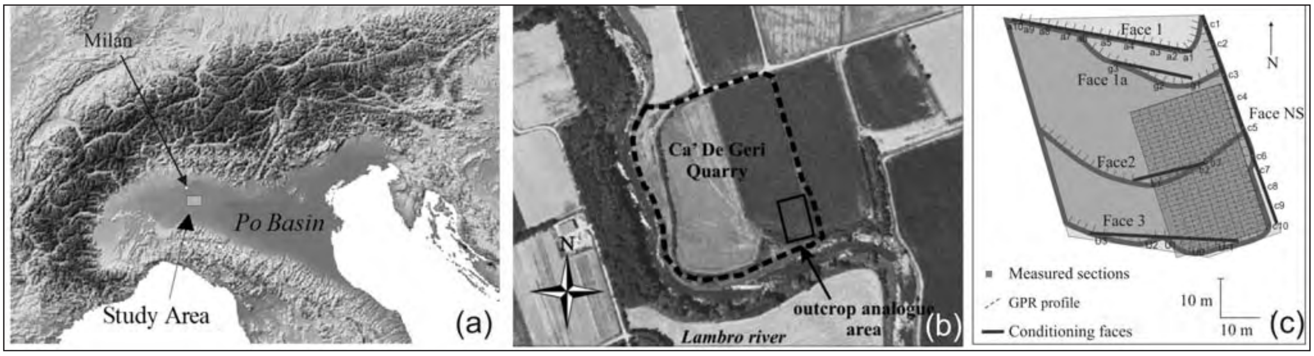

Fig. 1 - Location of the southern Lambro Valley (a) and of the studied quarry site (b); scheme of the study site. The location and orientation of the pit wall exposures (Face NS, Face 1, 2 and 3), of the 31 measured sections and of the GPR profiles is drawn (c).
- *Ubicazione della valle meridionale del Fiume Lambro (a) e del sito in studio (b); schema del sito di studio, con segnalate le posizioni degli spaccati misurati, delle 31 sezioni stratigrafiche di dettaglio e del rilievo GPR eseguito (c).*

the Upper Pleistocene sandur of the Lecco glacial amphitheatre. The quarry site exposes three superimposed depositional units formed by sands, gravels and subordinate silt and clay, which could be attributed to an historical age, as it was proved by the findings of Roman to Middle Age and Renaissance Age artifacts (bricks, tiles, ceramics), imbricated within dunes and bars (DELL'ARCIPRETE, 2005; BERSEZIO *et alii*, 2007). Two units correspond to the exposed parts of two composite point bars and channels with minor channel fills on top. We named them respectively unit A (the lower, with Roman-Middle Age findings) and unit B (the upper, with Renaissance Age findings). Unit A shows the lateral transition from a composite point bar to main channel fill, unit B is mostly represented by a composite point bar, with chute channel scour and fills on top. The erosion surface between them, tapered by lag deposits, is the α surface (fig. 2). A younger channel (unit C, bounded by erosion surface β and partly anthropogenic) eroded part of unit B and will not be considered here because of the very scarce observations. Together with units A and B, it is cut by the modern and present-day courses of the Lambro River. Units A and B are formed by a hierarchic arrangement of depositional units, from the 2nd order of bed-sets to the 5th order of the bar/channel systems, which determines the architectural heterogeneity of the aquifer analogue.

1.2. - PURPOSE

The goals of this study are the multi-scale reconstruction of the aquifer heterogeneity by the integration of geological and sedimentological, geophysical, geostatistical and numerical modelling methods and the evaluation of the efficiency of different geostatistical simulation techniques, as SISIM, MPS and T-ProGS. The problem is how these techniques can reproduce complexity, at different simulations scales, and in the extremely heterogeneous case of meandering river sediments.

2. - WORK PLAN AND METHOD

We have analysed a volume of approximately 30000 m^3 (47 m×75 m×8.6 m). We have studied (1) the entire volume and (2) a test volume of about 400 m^3 (11.4 m×11.4 m×2.85 m) cut into the whole volume.

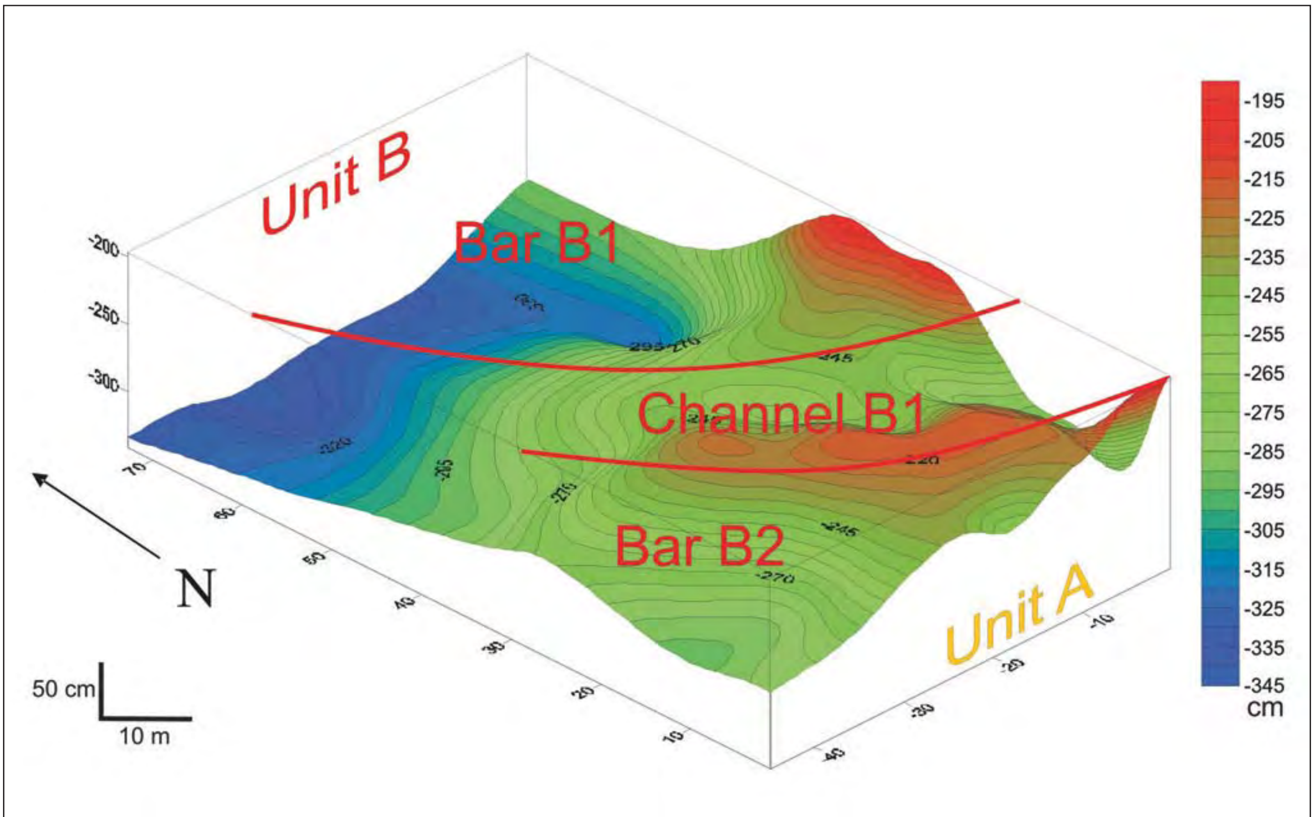

Fig. 2 - Kriged map of the erosional surface α between unit A and B obtained by GPR survey and stratigraphic logs. The colour scale indicates the depth of the α surface below the ground surface.
- *Mappa della superficie erosionale a di separazione fra le unità A e B, ottenuta per kriging dei punti quotati da rilievi GPR e sezioni stratigrafiche. La scala indica la profondità della superficie a rispetto al piano campagna.*

The data set consists in: i) images of five, almost orthogonal, quarry faces; ii) 31 vertical sedimentological logs with cm-scale resolution; iii) grain-size, porosity and permeability data of 5 facies classes (28 samples); iv) Ground Penetration Radar (GPR) and Vertical Electrical Sounding (VES) images of the volume.

At first, the geological and hydrostatigraphic model was elaborated, starting from the stratigraphical, sedimentological and geophysical analysis of the quarry volume. Facies mapping was performed in the field by measurement and sampling of the 31 detailed sedimentological logs and was supported by the analysis of the photo-composition of the quarry faces. In this way plan-view and vertical maps of the geometry, hierarchy and internal architecture of the sedimentary bodies were obtained. This model includes: i) the geometry and the hierarchic arrangement of the depositional units and of their bounding surfaces at different scales; ii) the distribution of the facies and the hydrofacies within the hierarchical arrangement of the stratigraphic units; iii) the hydrostratigraphical characterisation of the hydrofacies and the hydrofacies groups (porosity, permeability, continuity and connectivity); iv) the interpretation of the genesis and the evolution of the sedimentary bodies.

Then the volume was simulated with SISIM, T-ProGS and MPS. Conditioning data were taken from the vertical facies maps of the quarry faces (fig. 1c). For modelling purposes four hydrofacies were used, based on the analysis of *K* values obtained by samples: least permeable (F, very fine sand and silt-clay respectively from topmost channel-fill, silt/clay plugs, drapes and balls), low permeable (S, sand from point-bar and channel fill bedforms), medium permeable (SG, sandy gravel and gravelly sand from point bars) and most permeable (G, open framework gravels from the lower parts of the lateral accreted units). See table 1 for further details. The facies maps were discretized with square cells (0.05 m spacing) and variographic and transition probability description of correlation of hydrofacies were performed on the discretized domains.

The 3-D facies simulation was run on the entire volume, with "big cells" (0.4 m×0.4 m×0.1 m, coarse grid) and "small cells"(0.2 m×0.2 m×0.05 m, fine grid) and on the test volume with the fine grid. This test volume has been chosen in an area with many conditioning data, from two orthogonal faces, and covers part of the three units A, B and C (fig. 3).

Tab. 1 - *Facies classification adopted in this study, correlative hydrofacies and estimated permeability values.*
- Classificazione di facies adottata in questo lavoro, idrofacies operative e valori di permeabilità stimati.

Facies Class	Facies	Interpretation	Estimated K values (m/s)	Operative hydrofacies
F	Fm,	Clay plug, mud balls	$1*10^{-9} \div 1*10^{-6}$	F/fS
	Fl	Clay drapes		
S	Sh	Low-relief bedwaves, upper flow regime	$5*10^{-5} \div 5*10^{-4}$	
	Sm	Channel fills, lower flow regime		
	Sr	Ripples		
	St	3D sand dunes	$1*10^{-4} \div 1*10^{-3}$	S
	Sp	2D sand dunes		
	Sl	Sand drape		
SG	SGm	Avalanching (scroll bars and channel fills)	$5*10^{-4} \div 1*10^{-2}$	SG-GS
	SGt	3D gravelly sand dunes		
	SGp	2D gravelly sand dunes		
	SGh	Traction carpet, upper flow regime		
	SGl	Bedload sheets		
GS	GSm	Avalanching (scroll bars and channel fills)		
	GSt	3D gravelly sand dunes		
	GSp	2D gravelly sand dunes		
	GSh	Traction carpets, upper flow regime		
	GSl	Bedload sheets		
G	Gm	Avalanching (scroll bars and channel fills)	$1*10^{-2} \div 5*10^{-2}$	G
	Gt	Migration of 3D gravel dunes		
	Gp	Migration of 2D gravel dunes		
	Gh	Bedload sheets, upper flow regime		

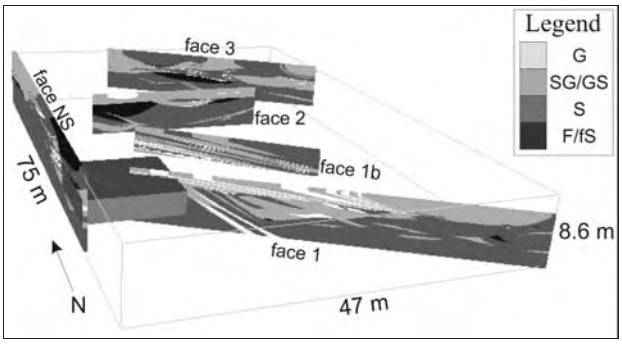

Fig. 3 - Vertical facies maps of the quarry faces. The test volume is drawn at the northern end of face NS.
- *Mappe di facies verticali della cava. Lungo la faccia NS è riportato il volume test utilizzato per le prove a scala molto fine.*

In order to evaluate efficiency and pitfalls of the different simulation techniques, at different operative scales, we have modelled the entire volume in two different ways: either simulating the undivided entire volume or simulating separately the units, then merging the simulations through the kriged α boundary between A and B.

Semivariogram computation and sequential-indicator simulations were performed using GSLib (DEUTSCH & JOURNEL, 1992); markov chains analysis and transition-probability simulation were computed with T-ProGS (CARLE, 1999) and multi-point- simulations were performed with CtMainMPSimListLDI code, developed by Straubhaar, Comunian and Renard (University of Neuchatel – CH).

Figure 4 shows an example of the computed semivariograms, of the transition probabilities graphs and of the training images.

At last we could compare the outcomes of several equiprobable realizations obtained by the different methods to each other and to the geological model, applied to different domains and at different scales. In this case quantitative objective validation was impossible. In fact hydraulic tests or tracer tests could not be performed on this aquifer analogue, located in an active quarry area. Therefore, the comparison between the geological model and the simulations was made by visual inspection and image analysis on the vertical facies maps and on sections cut through the simulated volume.

3. - RESULTS

In figure 5 the geological model is presented.

The results of the simulations obtained with the different methods applied to the entire volume, to the separate units and to the test volume, are exemplified in figures 6, 7, 8. On the test volume 50 equiprobable simulations were obtained with each method (fig. 6). On the entire volume we performed 10 realizations for each method using big cells (depositional elements scale, figure 7) and one realization for each method using small cells, for the whole volume and for the units A and B separately (fig. 8).

The observation of semivariograms and experimental transition probabilities, computed for the four hydrofacies on the entire dataset, shows a good correspondence between the semivariogram ranges and the experimental transition probabilities. This good correspondence occurs because both semivariograms and transition probability curves quantify the lateral continuity of the hydrofacies and our analysis is performed on several thousands of data continuously sampled along the vertical and horizontal directions in our indicator database. This dataset does not include the multiple sources of error typical of the databases consisting only of borehole logs (bias in estimates of facies proportion and spurious lateral indicator correlation, respectively due to clustering and sparse and non-random distribution of logs).

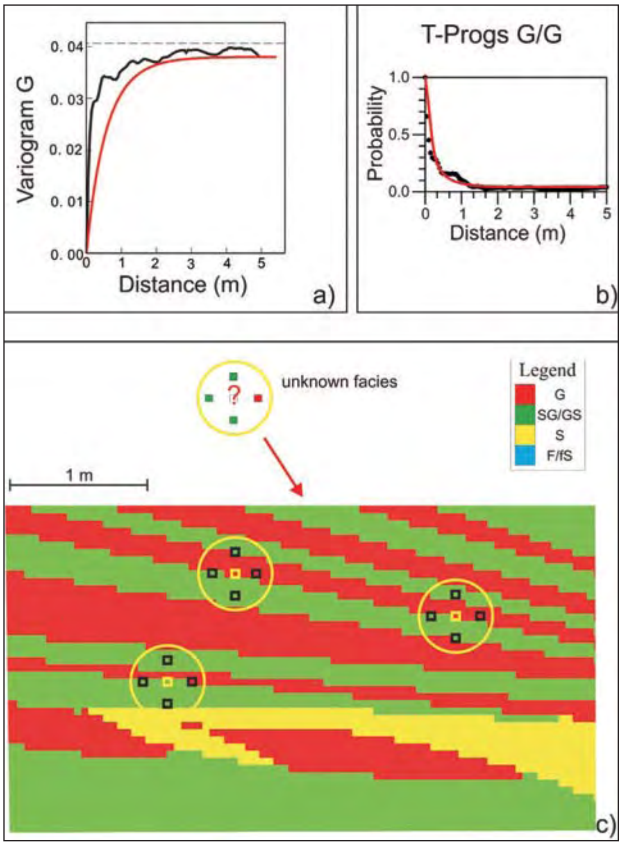

Fig. 4 - Example of semivariograms (a) and transitional probabilities (b) for the hydrofacies G (gravel) in the vertical direction; in black the experimental curves, in red the fitted models. (c) Example of training image.
- *Esempio di semivariogramma (a) e probabilità di transizione (b) per l'idrofacies G nella direzione verticale; in nero le curve sperimentali, in grigio le curve relative ai modelli adattati. (c) Esempio di training image.*

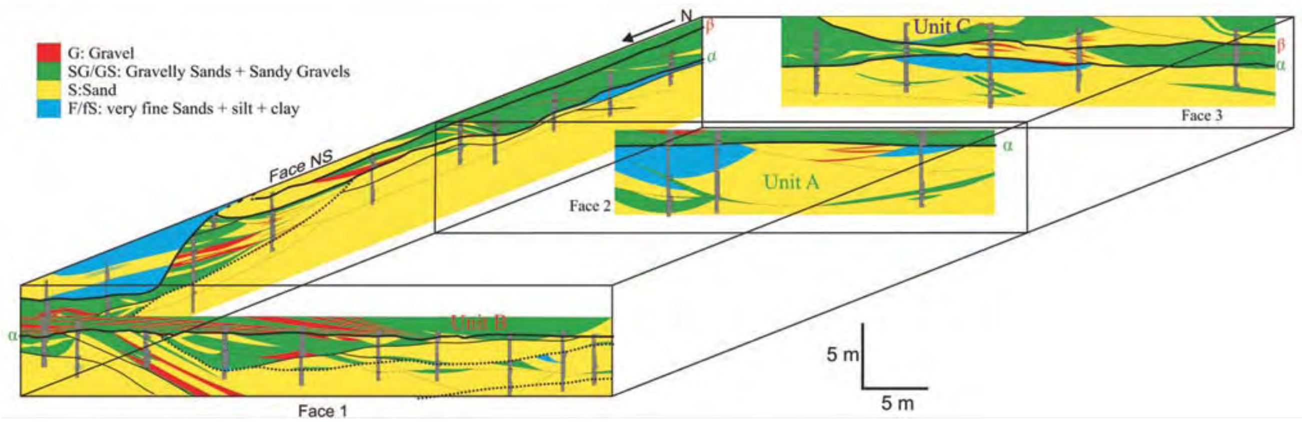

Fig. 5 - Geological model, that includes the shape and hierarchy of the depositional units and the distribution of the 4 operative hydrofacies (G: Open Framework Gravels; SG: Gravelly Sands and Sandy Gravels; S: Clean Sands and F: Sandy Silts and Clays).
- Modello geologico. Esso include la forma e la gerarchia delle unità deposizionali e la distribuzione delle 4 idrofacies operative (G: Ghiaie a trama aperta; SG: Ghiaie sabbiose e Sabbie ghiaiose; S: Sabbia pulita e F: Sabbia siltosa e argilla).

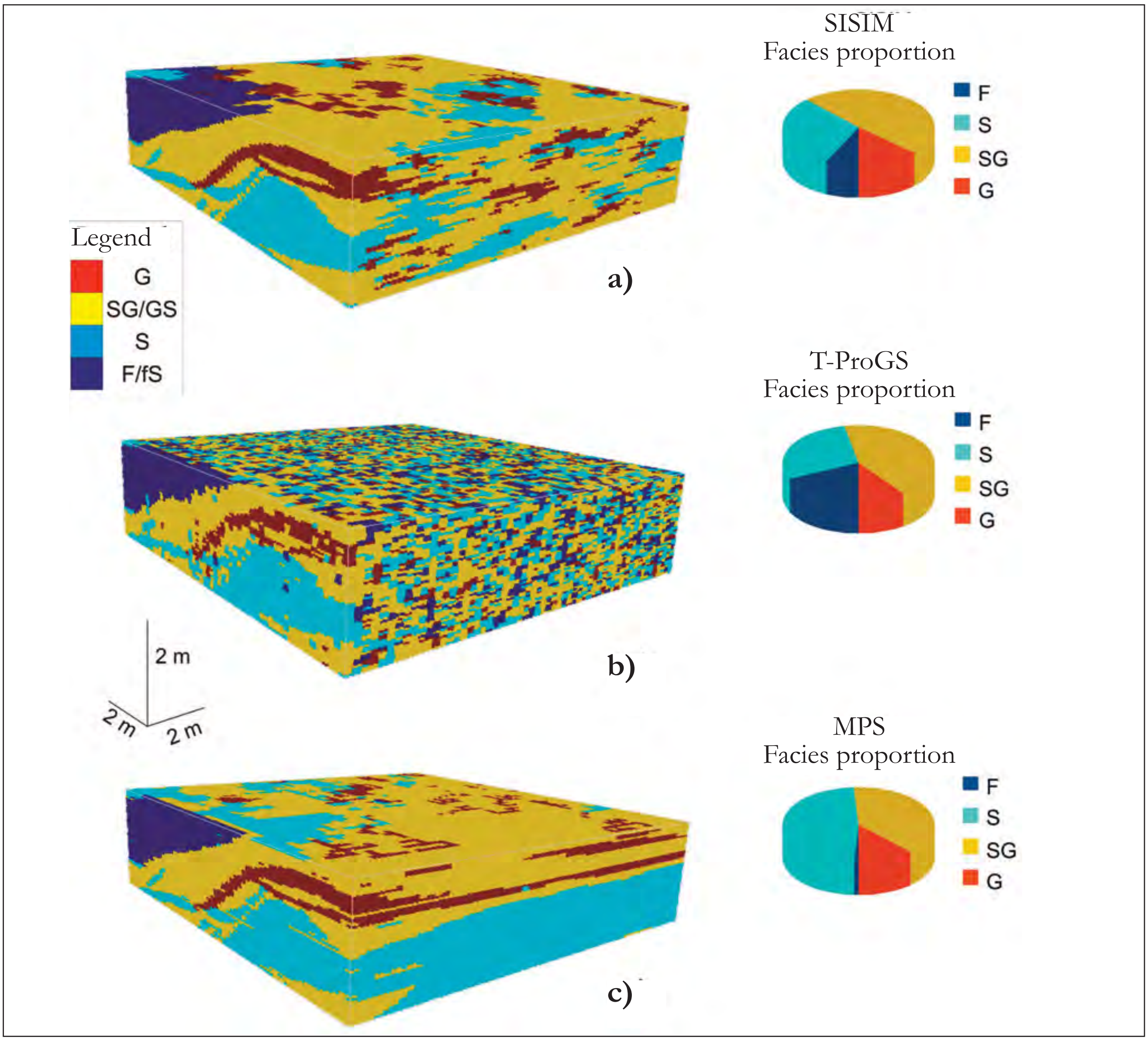

Fig. 6 - Equiprobable simulation number 1 of 50, computed in the test volume with (a) SISIM (b) T-ProGS and (c) MPS.
- Risultati della simulazione equiprobabile numero 1 di 50, ottenuta nel volume di prova con (a) SISIM (b) T-ProGS e (c) MPS.

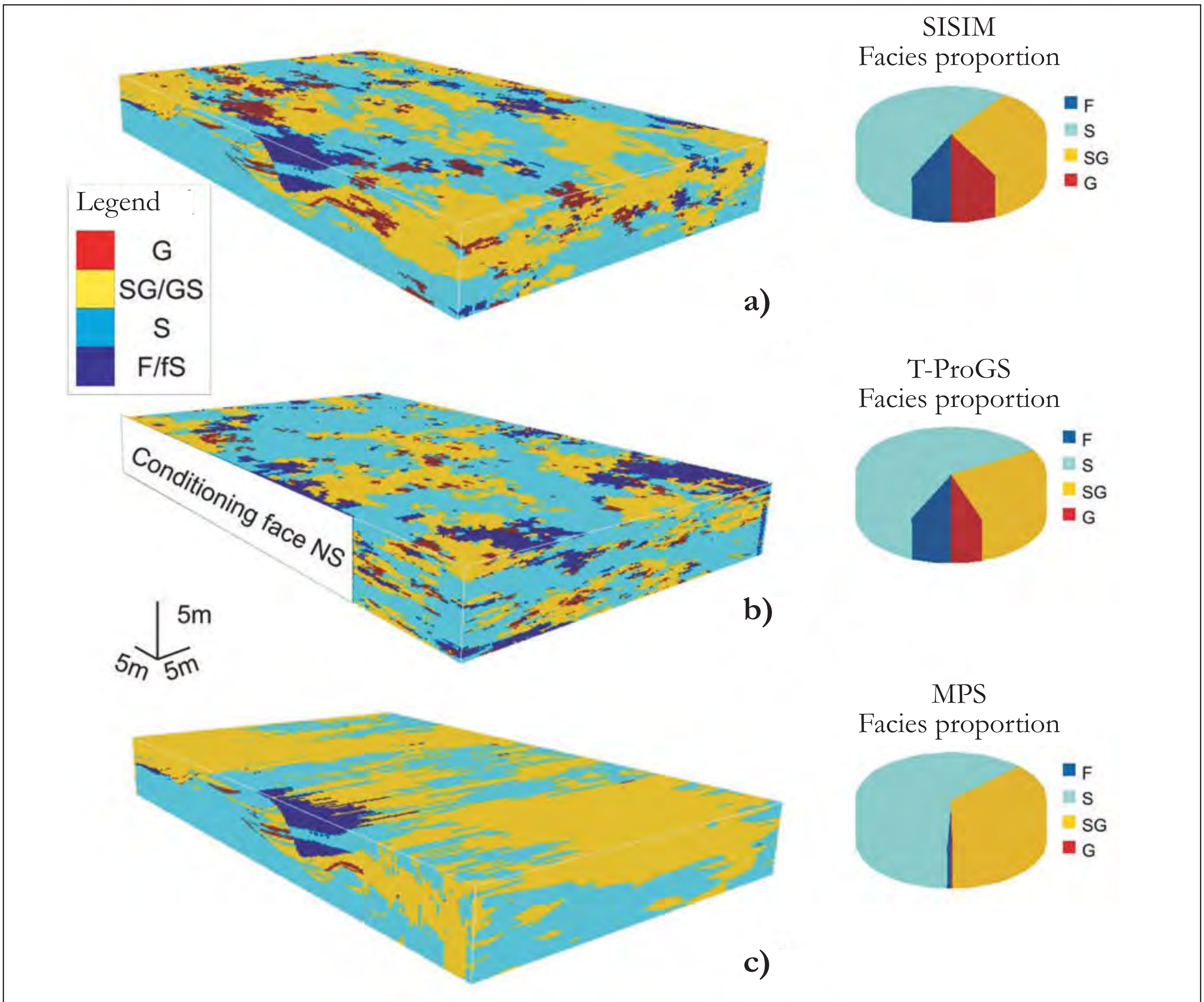

Fig. 7 - Equiprobable simulation number 1 of 10, computed in the entire volume (0.4 m×0.4 m×0.1 m cells) with (a) SISIM (b) T-ProGS and (c) MPS.
- *Risultati della simulazione equiprobabile numero 1 di 10, ottenuta nel volume intero (celle di 0.4 m×0.4 m×0.1 m) con (a) SISIM (b) T-ProGS e (c) MPS.*

4. - DISCUSSION

4.1. - COMPARISONS AMONG DIFFERENT REALIZATIONS

4.1.1. - *Depositional elements scale*

Probability of occurrence of each facies has been computed from the 10 realizations of the entire volume with each method (fig. 9). A connectivity analysis was also performed and applied to support the comparisons between simulations. In this study we used a connectivity parameter (total connectivity) that measures the probability that pairs of connected points belong to a subset characterised by a given property, e.g., texture or hydraulic conductivity, as proposed in VASSENA *et alii* (2009) (fig. 10). We have computed total connectivity for the test volume and for the entire volume both for small and big cells. For the simulations realized in entire volume with small cells, we have computed the connectivity indicators for moving blocks of 57×57×57 cells, to produce a moving average of the connectivity values.

The visual inspection and the connectivity analysis show that T-ProGS simulations generate a background of S hydrofacies voxels, connected in the whole volume, through which the other hydrofacies are sparse with low connectivity. On the contrary MPS simulations yield well connected volumes of SG hydrofacies bodies that alternate with the S hydrofacies bodies (fig. 11).

4.1.2. - *Facies scale*

The probability of occurrence for each facies have been computed from the 50 equiprobable simulations of the test volume (fig. 12). At this scale the following results can be highlighted:

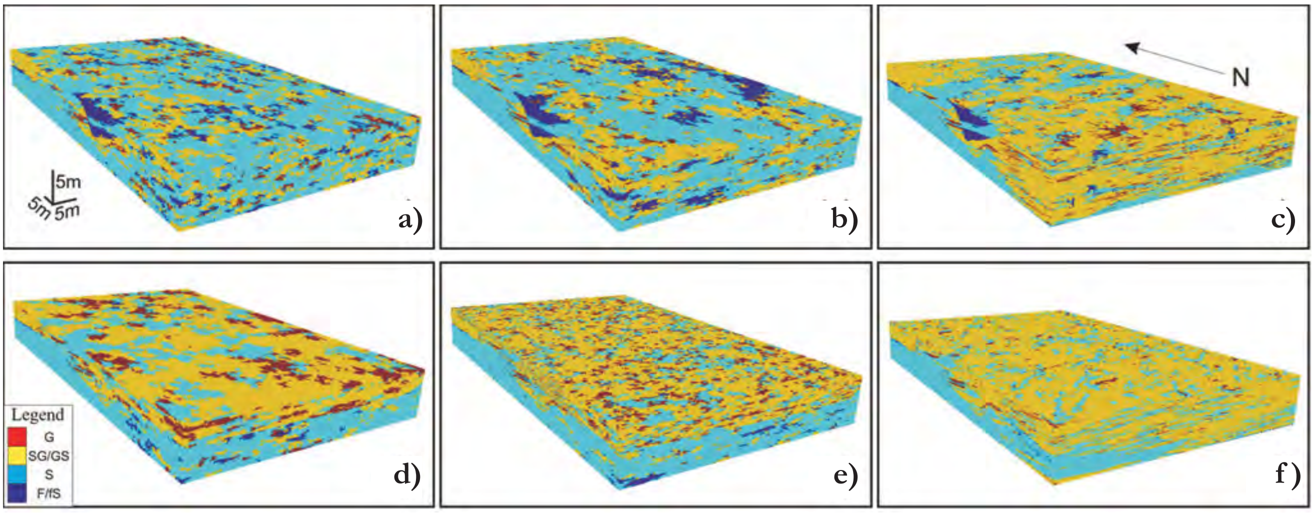

Fig. 8 - Simulations of the undivided entire volume (0.2 m×0.2 m×0.05 m cells) computed with (a) SISIM (b) T-ProGS and (c) MPS. Simulations of units A and B computed separately using (d) SISIM (e) T-ProGS and (f) MPS.
- *Simulazioni realizzate nel volume totale indiviso (celle di 0.2 m×0.2 m×0.05 m) con (a) SISIM (b) T-ProGS e (c) MPS; simulazioni realizzate simulando separatamente le unita A e B con (d) SISIM (e) T-ProGS e (f) MPS.*

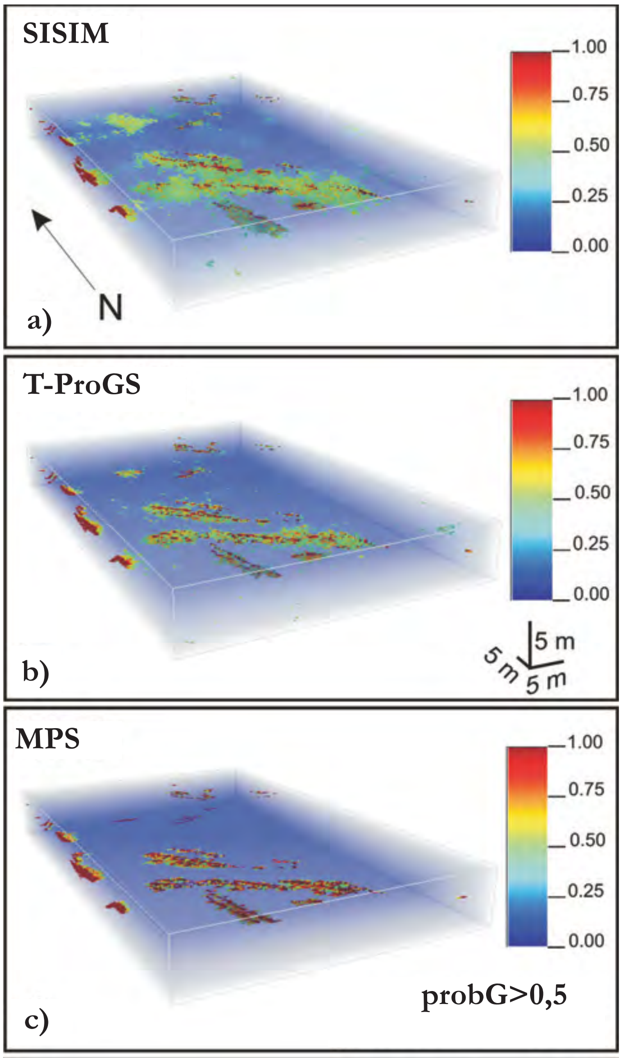

Fig. 9 - Probability > 50% to find facies G in each cell of the simulated entire volumes with (a) SISIM (b) T-ProGS and (c) MPS.
- *Probabilità >50% di trovare la facies G in ciascuna cella dei volumi totali simulati con (a) SISIM (b) T-ProGS e (c) MPS.*

It was almost impossible find a Markov Chain model fitting the transition probabilities statistics computed on the conditioning faces of the test volume, therefore T-ProGS simulations are unsatisfactory for all facies at this scale. At this scale, in fact, there are few repetitions of the facies bodies, therefore transition probabilities statistics are inadequate.

MPS simulations produce continuous facies bodies for the S, SG and G facies, that are the most abundant in the conditioning faces used to derive the training images; on the other hand the same simulations cannot take into account the geometry and distribution of the F facies bodies, that are present only in one of the orthogonal training images.

SISIM yields a good spatial continuity for all the facies bodies, but different equiprobable realizations lead to significantly different results.

4.2. - Comparisons to the geological model

Simulations obtained with different methods were compared to the geological model obtained from the analysis of the quarry exposures and yields the following results.

Visual inspection and comparison with field observations show that, for the simulations with fine grid of the entire volume, SISIM and T-ProGS yielded unrealistic results for the whole volume of units A and B. The realizations obtained by separate simulation of the two units were by far more realistic. On the contrary for MPS, the simulation of the undivided volume is more realistic than the simulation for the Units A and B separately. MPS method, in fact, can take in account the differences between units that are evident in training images.

To compare different simulations we performed a 2-D image analysis of the hydrofacies bodies, considering different parameters computed over the conditioning faces 1 and NS and on four sections cut into the SISIM- and T-ProGS- simulated volumes, parallel to the conditioning faces at increasing separation distances (DELL'ARCIPRETE *et alii*, 2009). The image analysis shows that when units A and B are simulated separately every technique underestimates the continuity and size of the low-rank geological elements (hydrofacies bodies). MPS simulations generate a quite smaller number of connected objects (i.e. hydrofacies bodies) than T-ProGS and SISIM for the simulations on the coarse grid. MPS too produces fragmented objects when applied to the fine grid.

The distribution of hydrofacies G (open framework gravels along the lower part of the inclined bed-sets of the composite bars) and F (meter-sized lenses of very fine sand and mud at the top of minor channel elements and decimeter-size mud clasts at their base) is not reproduced by T-ProGS simulations, that yield a scattered pattern of small clusters, within a "matrix" of facies S and SG. MPS yields better results for background hydrofacies then for the least abundant facies. Simulations by SISIM reproduced rather efficiently the size, shape, distribution and orientation (sloping features of lateral and frontal accreted elements) of these low-hierarchy elements.

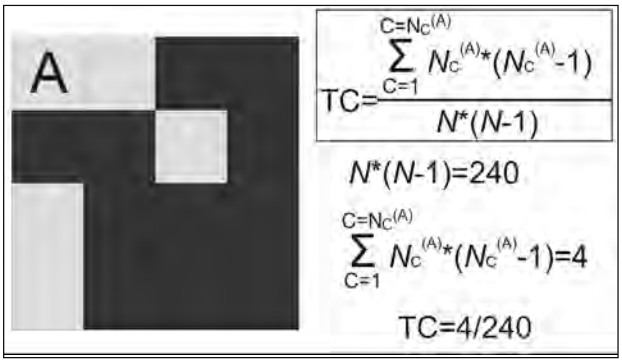

Fig. 10 - Total connectivity computation, according to VASSENA *et alii* (2009), where NC(A) is the number of connected points belonging to facies A; N is the number of points in the domain and TC is the total connectivity.
- *Calcolo della connettività totale, secondo* VASSENA et alii *(2009), con NC(A) numero di punti connessi appartenenti alla facies A; N numero di punti appartenenti al dominio e TC connettività totale.*

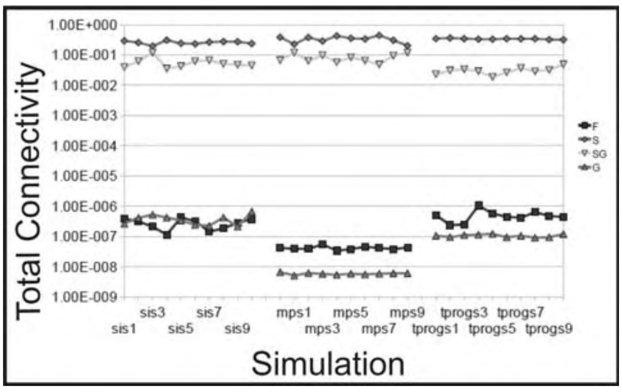

Fig. 11 - Total Connectivity computed in the entire volume (0.4 m × 0.4 m×0.1 m cells) with SISIM, MPS and T-ProGS.
- *Connettività totale calcolata nel volume totale (celle di 0.4 m×0.4 m×0.1 m) con SISIM, MPS e T-ProGS.*

The geological model shows a polarity of transition from GS and G hydrofacies association to S and less abundant F hydrofacies towards the western and southern part of the volume, where the bar to channel-fill transitions occur. This trend is only partially reproduced by simulations. Visual in spection of the simulated volumes reveals periodical repetitions of the most permeable facies G, at a separation distance that is multiple of the variogram range in the case of the SISIM, and of the minimum of transition probability in the case of T-ProGS. MPS yields repetitions of S and SG bodies, imitating their shape in the training images. In summary, all the simulation methods do not account for the non-stationary architecture of composite bars and channels and are not capable to reproduce their real spatial trends.

SISIM and T-ProGS do not reproduce the elements of the architectural complexity, like minor channels, erosion bases, etc. This problem affects many pixel-oriented methods of simulation and, in our case, it arises from the fact that the semi-variogram and correlation matrix are a bivariate isotropic measure (two-point autocorrelation), and therefore any non-linear correlation structure (e.g., curved surfaces) cannot be reproduced. MPS, on the contrary, can reproduce the shape of the curved structures, but cannot reproduce their internal features at this scale. Moreover, vertical tendencies at the scale of the bed-sets and bed-set groups (2–4 m), which are evident in the cross-variogram and in the off-diagonal vertical transition-probability plots of the facies maps, are partially lost in the 3D simulation. The representation of such non-stationary periodicities is still an open issue and cannot be resolved using "classical stationary" semivariogram or Markov chain models (FELLETTI *et alii,* 2006).

Observing the differences between the simulations performed on small and big cells we can notice that the use of small cells do not significantly improve the results. On the contrary in MPS the shape and the dimension of S and SG hydrofacies bodies are partly lost.

Connectivity analysis shows that the differences between units A and B are caught by connectivity indicators. For instance in unit B it is possible to observe the presence of oblique layers of connected open framework gravel (G) that were not simulated in unit A, consistently with the geological observations.

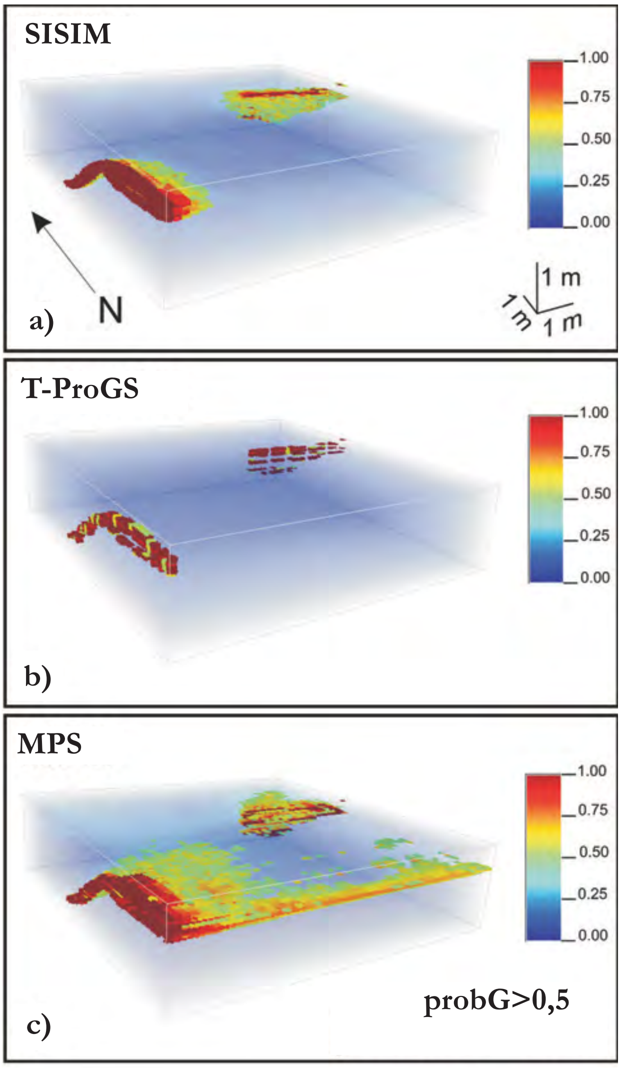

Fig. 12 - Probability > 50% to find facies G in each cell of the simulated test volumes with (a) SISIM (b) T-ProGS and (c) MPS.
- *Probabilità >50% di trovare la facies G in ciascuna cella dei volumi di prova simulati con (a) SISIM (b) T-ProGS e (c) MPS.*

5. - CONCLUSIONS

Simulation of fine-scale heterogeneity of aquifer analogues characterized by high textural and structural complexity is possible, but realistic results are by far difficult to obtain yet. However our attempts yielded realizations that show many similarities with the geological model. SISIM revealed itself more prone to reproduce size, continuity and shape of the low-rank elements of the sedimentary architecture (bed-sets or hydrofacies bodies) than T-ProGS. MPS can reproduce size, continuity and shape of the elements that are well represented in the orthogonal training images, but completely misses the poorly represented facies.

Simulations of the undivided volume, obtained by SISIM, T-ProGS and MPS, are unrealistic because units A and B are characterized by very different statistical properties (frequency and correlation of hydrofacies). In fact realistic simulations can be obtained if statistical properties do not vary significantly throughout the studied domain (FALIVENE *et alii*, 2007). Therefore, at any scale, a preliminary detailed delimitation of the hydrofacies bodies to be reproduced is a primary need.

Both the studied composite bar and channel systems are characterized by facies trends that introduce non-stationarity. All methods we used reproduce non-stationary features only in an indirect way, accounting for facies proportions of the conditioning faces. How to account for depositional trends that are associated with periodicities at different scales, as is the case of point-bar complexes, looks to be an open problem in such a case.

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