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IMPACT OF A CONCEPTUAL MODEL FOR PRESERVED EOLIAN BEDFORMS, DEVELOPED FROM TRONCOSO INFERIOR MEMBER OUTCROPS, IN GEOCELLULAR RESERVOIR MODELING TASKS

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RESUMEN

Impacto de un modelo conceptual para formas de lecho eólicas preservadas, desarrollado en afloramientos del Miembro Troncoso Inferior, en tareas de modelado geocelular.

Las heterogeneidades petrofísicas típicas de los reservorios de hidrocarburos de origen eólico pueden cobrar una importancia creciente en etapas de desarrollo avanzadas (EOR). Por otro lado, las sucesiones eólicas se caracterizan por presentar una arquitectura sedimentaria compleja que históricamente ha retrasado la elaboración de modelos conceptuales coherentes sobre su desarrollo. Esta complejidad hace que la predicción del diseño de heterogeneidad de estos reservorios en la escala interpozo sea un reto considerable. A su vez, muchos reservorios eólicos alrededor del mundo se caracterizan por una preservación "excepcional" de la topografía del sistema (Fm. Huitrín y Tordillo en la Cuenca Neuquina, Rotliegend del Mar del Norte, Fm. Norphlet del Golfo de México), permitiendo la preservación de distintos sectores de las formas de lecho con una arquitectura sedimentaria característica. La disponibilidad de un modelo conceptual de la arquitectura de un draa lineal de preservación excepcional, desarrollado a partir de la caracterización del registro del Sistema Eólico Troncoso (Mb Troncoso Inferior, Fm Huitrín, Cuenca Neuquina), puede generar un impacto considerable en la construcción de modelos geocelulares de este tipo de reservorios en el subsuelo. En este contexto, el objetivo de este trabajo es identificar las estrategias a aplicar en tareas específicas de la construcción de modelos geocelulares de subsuelo, a partir de un modelo conceptual generado previamente en afloramiento. Dicho impacto se evaluó de distintas maneras. Se construyeron modelos geocelulares para evaluar la practicidad de representar elementos de heterogeneidad de distintas escalas y que permitieron contrastar los resultados de honrar o no el modelo geológico. Finalmente, en base a modelos tridimensionales de la arquitectura sedimentaria, se pudo sugerir direcciones de máxima permeabilidad para cada estilo de arquitectura en función del elemento de heterogeneidad que generase un mayor impacto en la migración de fluidos (como superficies internas o planos de estratificación). En base a esta metodología, se evaluó el impacto de honrar el modelo geológico tanto en etapa de zonación, como en la construcción de una grilla geocelular, el modelado de cuerpos y/o facies sedimentarias y finalmente en el poblado de propiedades petrofísicas. Se espera que esta contribución colabore aportando información valiosa para asistir al modelado de este tipo de reservorios, no solo en la Cuenca Neuquina, sino también en otras cuencas alrededor del mundo.

INTRODUCTION

Subtle petrophysical heterogeneities typical of hydrocarbon reservoirs of eolian origin can gain a progressively larger impact upon fluid flow in mature development scenarios, for example during production with EOR techniques. This can give rise to a considerable source of uncertainty since the design of eolian sedimentary heterogeneity, its sedimentary architecture, is usually extremely complex. This complexity has historically delayed coherent conceptual models on the development of eolian sedimentary architecture (Mountney 2006). Furthermore, many eolian successions are characterized by the preservation of bedform topography. This not only conditions the external geometry of the reservoir interval, it also allows for the preservation of particular zones of the dune's sedimentary architecture that wouldn't be present on normal preservation conditions (i.e. bedform climbing).

From all of the above, it is clear that predicting the heterogeneity design of these successions in the interwell area can be a considerable challenge. The availability of a conceptual model developed from outcrops of a linear draa record in the Troncoso Inferior Member, can provide an important starting point to seek geocellular model-building strategies for this reservoir type. The objective of this study is to identify strategies for geocellular modeling of a preserved linear dune's rock record in the subsurface, based on a conceptual model developed from outcrop exposures.

METHODOLOGY

This paper first presents a previously developed geological model for a specific type of eolian bedform, and later evaluates how this model may impact reservoir geology characterization and modeling strategies in the subsurface. The workflow followed to develop both the geological model and the methodology used in its evaluation is presented (Fig. 1).

Development of the geological model

The geological conceptual model for the sedimentary architecture of linear bedforms used as the basis of this paper was developed from the multi-scale characterization of the Troncoso Eolian System record's outcrops (Argüello Scotti 2017) located in the southern Pampa Tril Plain. The mentioned eolian system record is part of the Troncoso Inferior Member of the Huitrín Formation, in central/northern Neuquén Basin (Groeber 1946; Legarreta 1985). The deposits that comprise the record of this eolian system are characterized by exceptional preservation of bedform topography (Masarik 2002; Veiga et al 2005) which allows for identification of large and small-scale bedforms in outcrop (Argüello Scotti and Veiga 2015) and in the subsurface (Dajczgewand et al 2006). The excellent quality of the record's exposure makes it an ideal candidate to develop a conceptual model for this type of scenarios.

The record of the Troncoso Inferior Member at the Pampa Tril locality was studied first as part of a regional study, in which the interval was characterized by field logs recording the most important sedimentological features of the deposits, and later interpreting basic depositional processes and accumulation systems by facies and facies associations analysis (Argüello Scotti 2017). This study allowed for the Troncoso Eolian System record identification and delimitation, followed by detailed characterization at different scales focused at a single large-scale preserved bedform. At the local scale, bedform topography was mapped, using a total station survey and virtual outcrops, allowing for a morphometric characterization of the preserved bedforms. At a sedimentary body scale, the sedimentary architecture was mapped over photomosaics and later checked by direct outcrop observation, while bounding surface dip azimuth readings, sedimentary body scale and shape was analyzed from direct outcrop observation and indirect

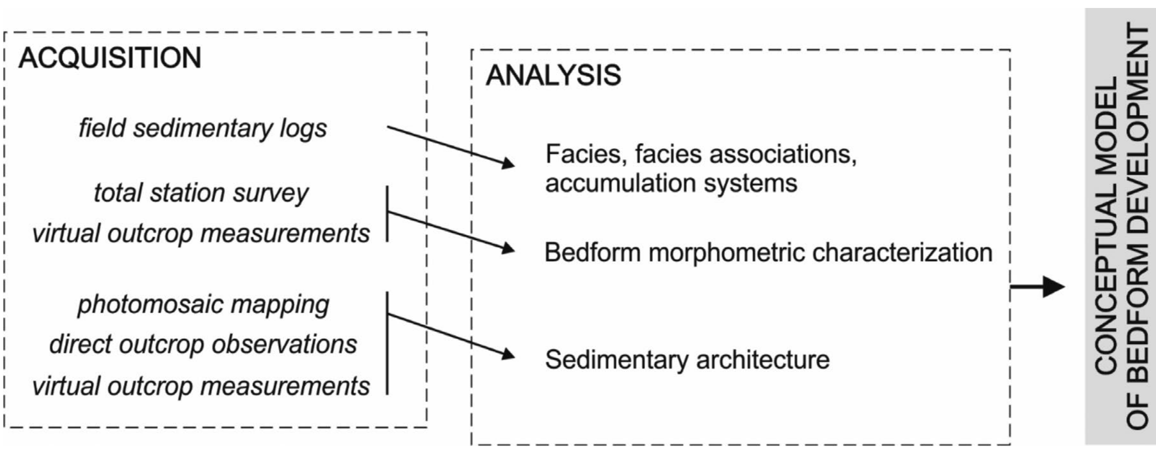

Figure 1. General workflow followed to develop the conceptual geological model.

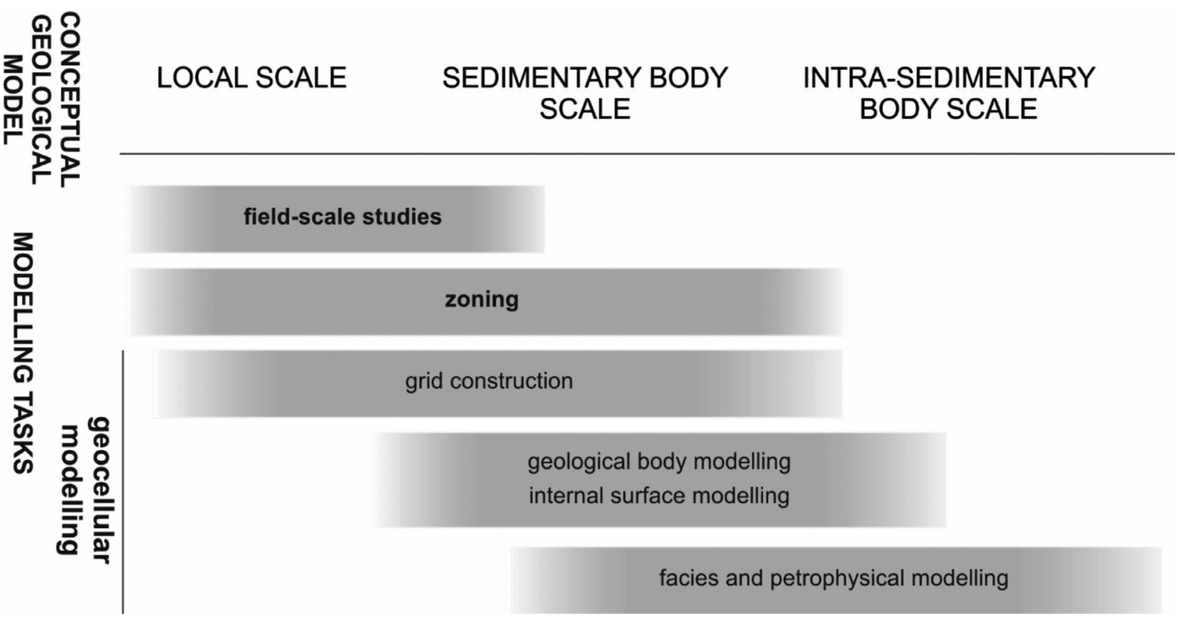

Figure 2. Scheme followed to analyze the impact of the conceptual geological model over typical subsurface modelling tasks.

virtual outcrop model (VOM) inspection. Finally, at the intra sedimentary body scale, cross-bedding and stratification types present within sedimentary bodies were analyzed from direct observation and once again from VOMs. This data allowed the identification of different styles of sedimentary architecture within the record, referred as architectural complexes. The origin of these complexes was analyzed by deterministic modeling, their distribution and abundance, and relative chronology of their sedimentary bodies. The result is a conceptual model of both the bedform's internal architecture and of the development history that led to its formation.

Evaluating the impact of the geological model

In order to fulfill the study's aim, the possible impact of the multiscale model over reservoir zoning, grid construction, geological body and/or facies modeling, and petrophysical modeling tasks was evaluated (Fig. 2). For each task, possible modeling strategies are suggested in order to represent sedimentary heterogeneity of different scales more realistically. Many of these suggestions are based on modeling examples generated using reservoir modeling software and BEDFORMS (Rubin 1987) open-access software. The results of these models allowed discussing the feasibility of representing heterogeneities of different scales with current reservoir modeling software, and to evaluate the potential impact of representing such heterogeneities on production forecasts. Scenarios where the sedimentary architecture of a linear dune does not match the type of architecture depicted in conceptual model are not addressed. These cases can be identified by cross-bedding dip-azimuths, and their internal architecture will be similar to that of the more familiar transverse bedforms (Rubin 1987; Rubin and Hunter 1985). Therefore, modelling strategies for those scenarios are not further explored in this paper.

THE GEOLOGICAL MODEL

The conceptual geological model (Fig. 3) summarizes the different scales of sedimentary heterogeneity expected for the record of preserved linear dunes of a concentric architecture style (Argüello Scotti and Veiga 2018). At the local-scale, it shows the expected geometry, dimensions and detailed shape of the interval of interest in these scenarios. Relatively flat, and slightly convex upwards, crestal areas (typically free of reworked facies) pass to the more steeply inclined flanks and the concave upwards plinths, eventually passing into flat interdune areas. At the sedimentary body and intra-sedimentary body scale, it shows how the sedimentary architecture of preserved linear dunes is most likely conformed by multiple sedimentary complexes with particular characteristics. Although the expected variability of sedimentary facies types in the dune bodies is low (mainly composed well-sorted sandstones with cross bedding of variable inclination angle and stratification types), significant differences in their shape and size are expected. In the Troncoso Member outcrop characterization these differences were stablished statistically (via analysis of variance tests, values provided in Argüello Scotti 2017, Argüello Scotti and Veiga 2018). These are interpreted as the result of different bedform configurations. The resultant conceptual model suggests that, while complexes resulting from simple dune configurations are found in the bedform record core, complexes resulting from compound/complex bedforms (dunes with superimposed dunes) are found in the bedform record periphery. The results of analysis of superposition and extension of both sedimentary complexes and the sedimentary bodies within them, and of bounding surface dip azimuth, show that deposition of the bedform record is characterized by expansion from a central core.

As a result, the model represents what is referred to as a concentric style of architecture. This is regarded as an end member in a scheme of possible linear bedform internal architecture, with the opposite endpoint being an asymmetric style. In cases of exceptional bedform topography preservation, both styles of architecture are thought to be likely. Evidence suggests that the development of this particular type of architecture is related to growth and longitudinal behavior of the bedform, as opposed to a sustained lateral migration in an asymmetric type of sedimentary architecture (Argüello Scotti, 2017). Cases of linear dunes with an asymmetric type of architecture, as indicated in the methodology section, closely resemble the internal architecture of transverse bedforms and are not further explored in this paper.

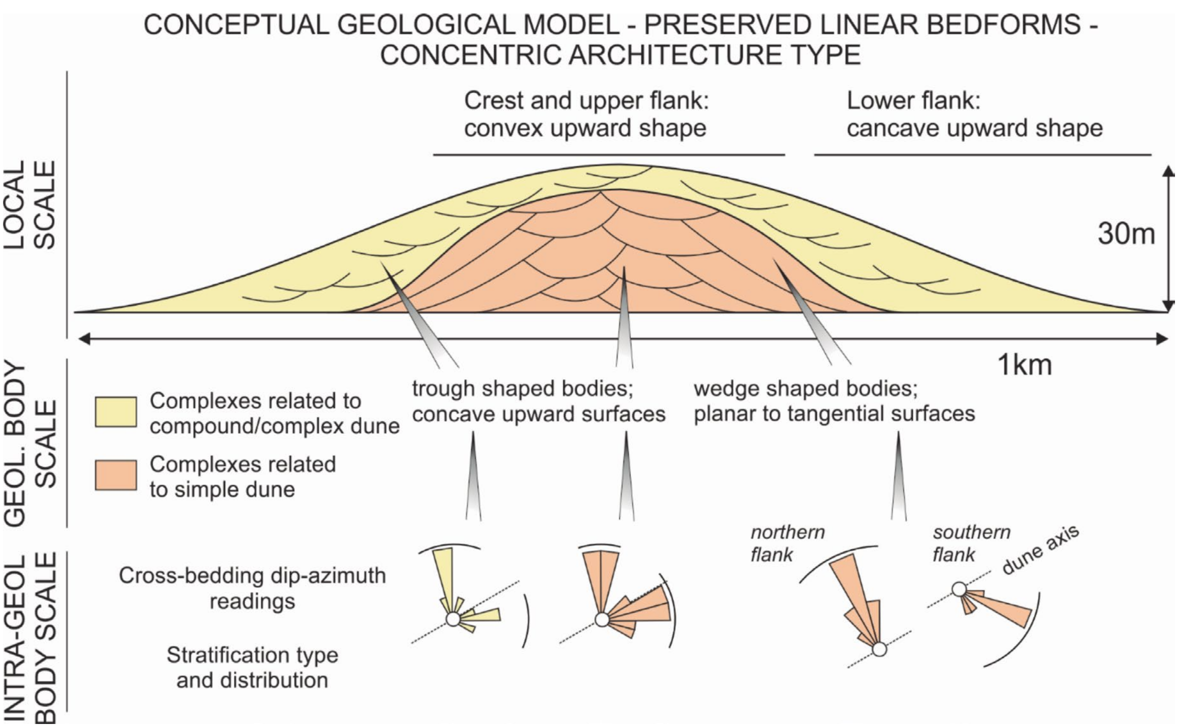

Figure 3. Conceptual geological model for linear megadunes (draa) of concentric type of architecture (Argüello Scotti, 2017). Some of the most remarkable aspects of the record's heterogeneity at each scale are summarized.

IMPACT ON FIELD-SCALE RESERVOIR STUDIES

The morphometry associated to the conceptual model at a local scale has an impact on prediction of the reservoir interval geometry and volume, as well as to the interval's hydraulic connectivity on a field-scale.

The major morphometric parameters of bedforms within the same eolian system, such as spacing, height, width and equivalent sand thickness, have been shown to follow well-defined relationships in modern examples, regardless of dune type (Al-Masrahy and Mountney 2013; Bullard et al 2011). Therefore, stablishing these relationships, as has been done for the Troncoso Eolian System specifically, can certainly aid critical predictions in new fields. For example, equivalent sand thickness (average sand thickness, easily translated to reservoir volume) could be predicted from dune spacing or width obtained from seismic data, with very little well coverage.

Regarding reservoir connectivity at a field scale, the usual morphology of these bedforms, characterized by a remarkable along-crest continuity (of over 10 km) indicate that connectivity will be favorable in crestline direction along the bedforms. Perpendicular to bedform crestline direction however, connectivity will be conditioned by multiple factors, the first of which will be the actual continuity of the reservoir interval in the interdune area. In the presented conceptual model, the eolian system record completely thins out in the interdune, indicating no net accumulation conditions. Although some reports of linear dune fields with net accumulation have been reported (Clemmensen 1989), most linear bedforms in modern sand seas are associated with sand bypass and null accumulation conditions. In this case, considering a seal rock above the reservoir, connectivity between the bedforms will depend on the nature of the deposits directly underlying the reservoir. If accumulation is registered in the system, then the reservoir unit will not thin out in interdune areas, and hydraulic connectivity between bedforms will be conditioned by interdune facies. Most likely, the wetter the interdune deposits, the most unfavorable will be such connection.

IMPACT ON RESERVOIR ZONING

If we consider reservoir zoning oriented to identifying intervals of relatively homogeneous design of geological heterogeneity, for further geocellular modeling using a specific method (Dubrule 1998), the presented geological model can provide many insights.

The regional-scale, conventional sedimentological study that framed the geological model, has a clear impact on zoning. Identifying and marking the boundaries between the record of different accumulation systems proved key for a more realistic reconstruction of the stratigraphic framework in the case of the Troncoso Member (Argüello Scotti and Veiga 2015). In remarkably complex facies distributions typical of continental scenarios, and especially in eolian and eolianfluvial interaction systems, adequate outcrop analogs can be an excellent aid to get a glimpse of the range of possibilities of subsurface reconstructions (Fig. 4).

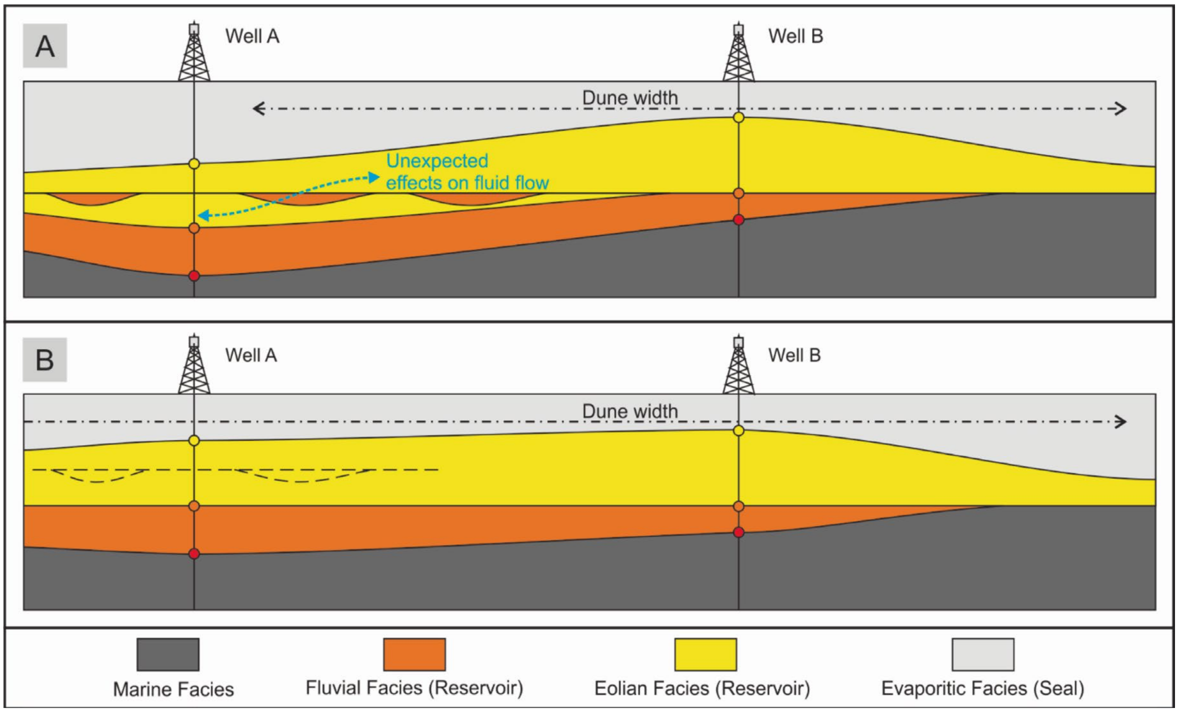

Figure 4. Example of the impact of conventional sedimentological and stratigraphic studies in reservoir zoning. Two possible interpretations for the same drilled sequence in a hypothetic subsurface scenario for the Troncoso Inferior Member (Argüello Scotti and Veiga 2015), the horizontal distance between the two wells being in the order of 102m. Note the impact in the reconstruction of the preserved eolian morphology and in the uncertainty in the distribution of sedimentary heterogeneity. A) Interpretation considering the presence of multiple eolian sequences. B) Interpretation failing to differentiate between different eolian sequences.

Local scale features of the geological model can have an impact in zoning as well. Firstly, the conceptual model provides a detailed characterization of the geometry of the eolian system record, most likely equivalent to the reservoir. This is valuable information in order to choose interpolation strategies when mapping the surfaces that bound zones in subsurface models. Regarding the top surface of the system record, the model lets us predict that, if bedforms are preserved after reworking by flooding, the crest of will have a gentle convex upwards shape, usually free of irregularities. This is the result of the bedform's sand destabilization and remobilization after saturation with water and also of wave action, that modify the dune crest's original profile (Strömbäck et al 2005). The flank areas on the other hand, will have a concave upwards shape, and are far more likely to have superimposed irregularities by preserved superimposed bedforms or by resedimentation deposits. Irregularities produced by preserved superimposed dunes have been shown in the Troncoso example to have up to 8m in height and over 100m wavelength. Such irregularities can also be found in the interdune areas (Argüello Scotti and Veiga, 2015).

Secondly, in the case of a system with net accumulation, a precise mapping of the system's record geometry will be helpful to separate exceptional preservation and normal preservation intervals. Even if both intervals are associated to deposition by the same eolian system, the sedimentary architecture and even early diagenetic conditions, will be greatly different in each interval (Fig. 5). Therefore, sectors with different type of preservation are excellent candidates to comprise particular zones in the model, since they will have distinct styles of sedimentary heterogeneity. Generalizing this further, the accumulation surface (i.e. the surface that joins interdune lows) will always be a strong candidate for a zone boundary at any possible scenario. Adding the exceptional preservation interval (i.e. interval above the accumulation surface) in the same zone with underlying deposits will most likely merge very different styles of geological heterogeneity, while on the other hand, mapping the accumulation surface is a very simple, straightforward task.

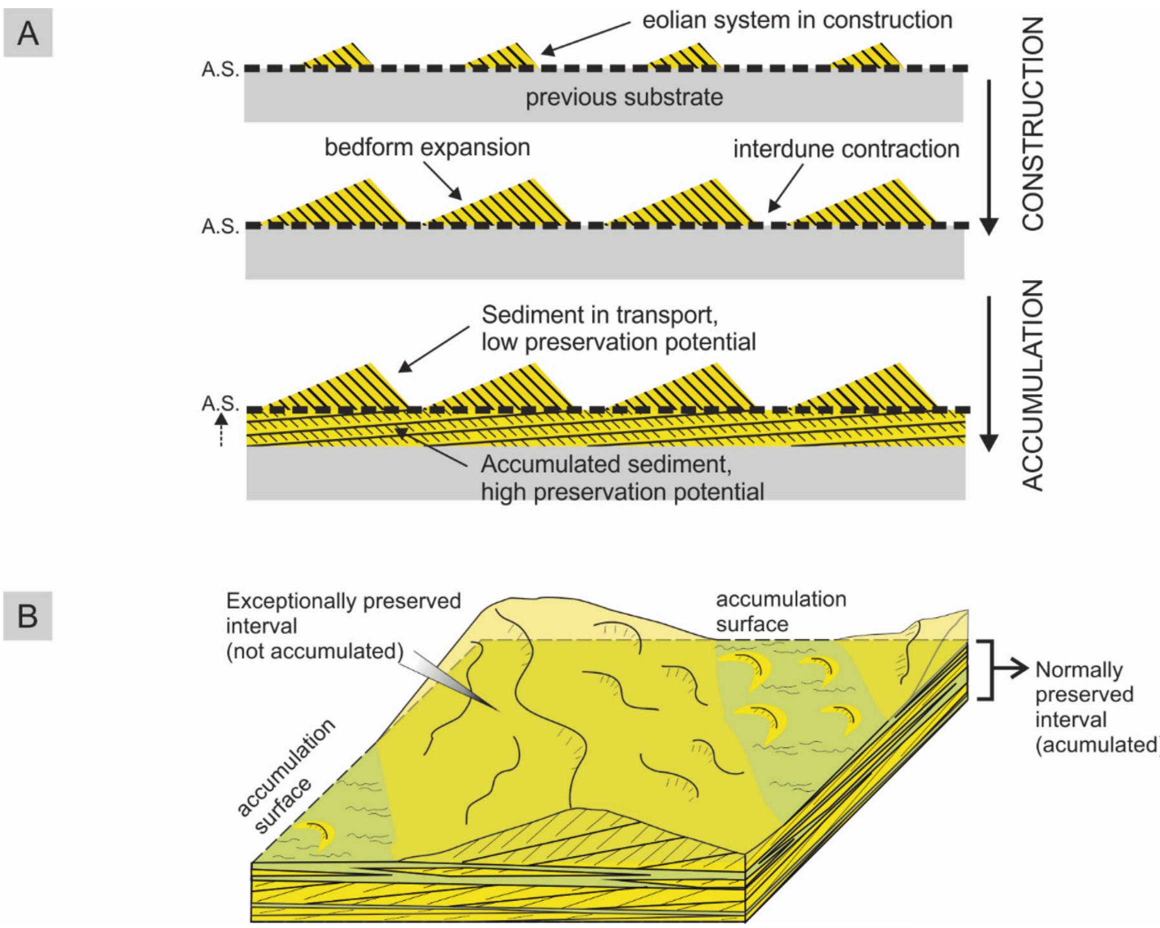

Figure 5. Differences between intervals of exceptional and normal preservation. No scale implied, as it is applicable to all bedform scales. A) Scheme of dune system construction and accumulation stages as defined by Kocurek and Havholm (1993) and Kocurek (1999). The accumulation surface is the surface that joins the interdune lows, which only rises once net accumulation is achieved in the system. B) Diagram showing the possible differences in sedimentary architecture between intervals with different type of preservation of the same system.

Finally, the sedimentary body scale heterogeneity in the conceptual model could also have an impact on reservoir zoning. The conceptual model shows how the record of the bedform is made up of different architectural complexes, each one of them with its own design of sedimentary architecture (sediment body scale and shape, bounding surface design, among others). If eolian sedimentary heterogeneities are suspected to influence fluid flow, then each architectural complex should comprise a distinct zone in the model, modelled by a specific method. The scale of the complexes would allow such strategy (Fig. 6). The most important drawback however, would be the actual identification of the complexes from subsurface data. 1D information from wells will likely not be enough to detect the complexes in a straightforward manner. The presence of different architectural complexes can only be suggested by analyzing cross-bedding and bounding surface dip azimuths in wells (dipmeter, borehole imaging), and stratification types in cores (Romain and Mountney, 2014).

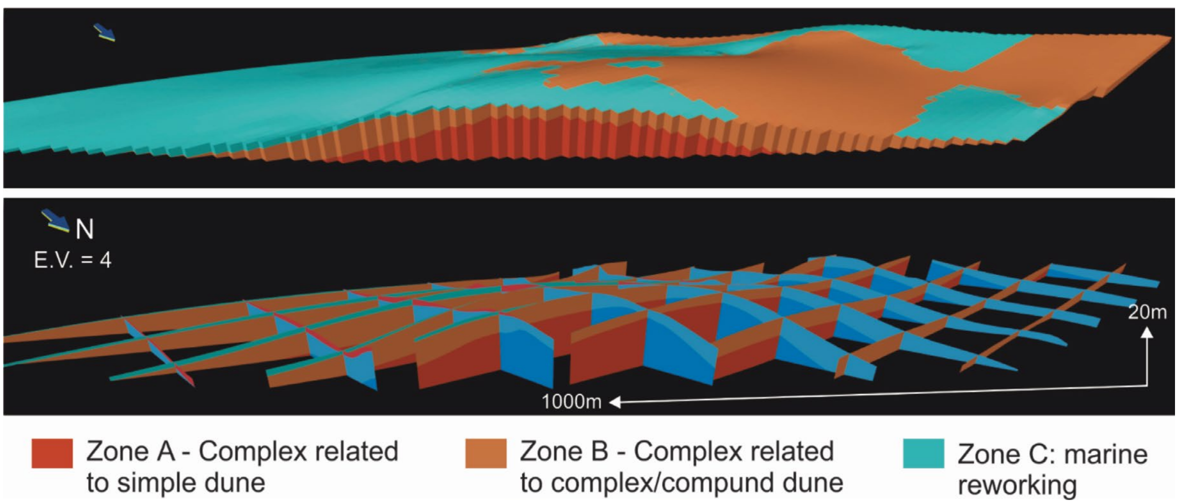

Figure 6. Geocellular model developed directly from outcrop data of the Troncoso Inferior System in the Pampa Tril outcrop. The scales of the architectural complexes allow their modelling as specific reservoir zones if necessary.

IMPACT ON GEOCELLULAR MODELING

As suggested earlier in this paper, most of the geological model's impact on geocellular modeling is given by sedimentary body and intra-sedimentary body scale heterogeneities. However, local scale features are also important in this regard, because the model shows a clear relationship between external bedform record and internal sedimentary body features. For example, bounding surface dip azimuths are dependent to their position within the preserved bedform; and sedimentary bodies within complexes related to simple dunes are trough shaped in the bedform crest and wedge-shaped in the bedform flanks, among other examples

Grid construction

Sedimentary body scale heterogeneities of the conceptual model show that both architectural complexes and sedimentary bodies themselves have a concentric distribution, as a result from deposition from a core outward. The oldest deposits are located in the bedform core, and the younger deposits are progressively located on the bedform peripheries (Fig. 3). In this regard, it is suggested that a top-conform grid, with cells of constant thickness, will be an appropriate strategy to accurately represent the sedimentary heterogeneity of the zone that contains the interval of exceptional preservation.

To test this suggestion, a hypothetical subsurface scenario was modeled. Zones were modeled by mapping surfaces that would honor the shape and dimensions depicted in the local scale conceptual model. Two grids with different strategies were built for the exceptional preservation interval (Fig. 7). Both grids had cells of uniform 1m thickness, but while one grid was top-conform, the other was base-conform. Using actual well logs from the Troncoso Inferior Member's exceptionally preserved interval, petrophysical properties (porosity and permeability) were spread to the grid by kriging, in order to better appreciate the impact of grid-building strategy in a resulting model. Once populated, the difference between both grid models is dramatic. The top

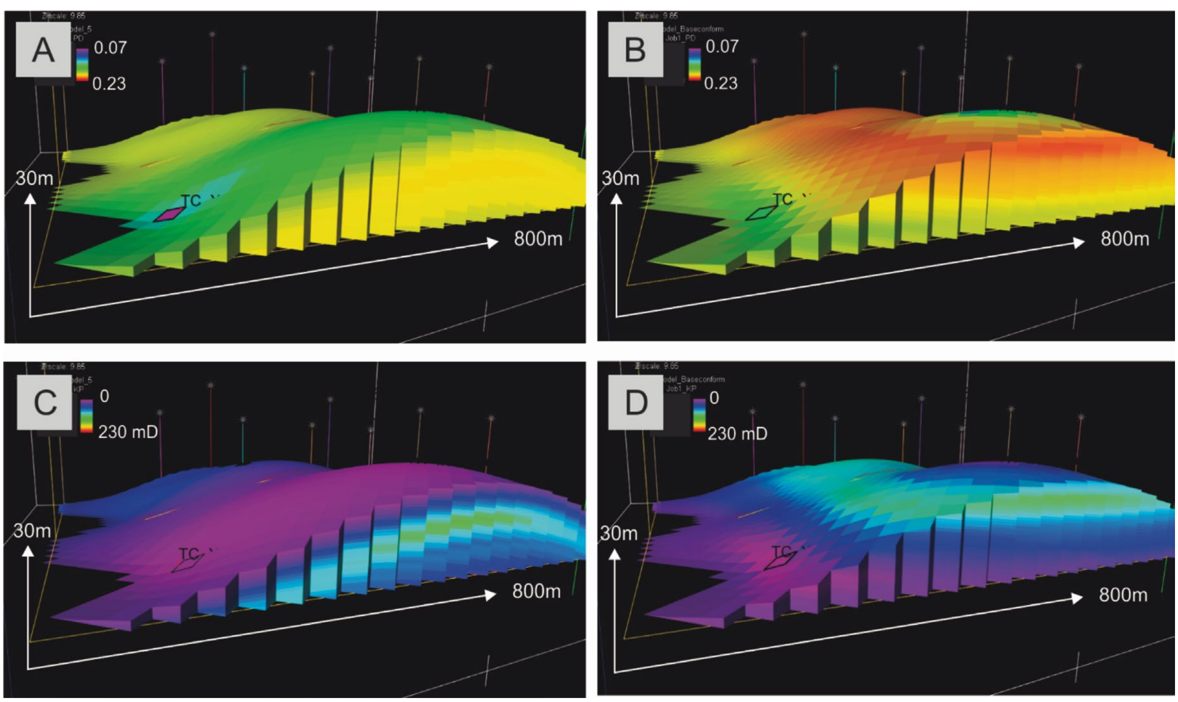

Figure 7. Impact of the conceptual model in grid construction. Modelling of a hypothetic subsurface scenario for an exceptionally preserved eolian interval with linear bedforms. The external geometry of the interval is based on the conceptual model. Two grids were modelled to contrast the results of a top conform grid against a base conform grid and the conceptual model. Both grids are of uniform cell thickness. Petrophysical values are spread from two wells with actual well values in the interdune and dune sectors. A) Result of porosity propagation with kriging in the top conform grid. B) Result of porosity propagation with kriging in the base conform grid. C) Result of permeability propagation with kriging in the top conform grid. D) Result of permeability propagation with kriging in the base conform grid.

conform grid propagates values parallel to the top boundary, correlating sectors between the dune crest and plinths. The base conform grid on the other hand, correlates the dune plinths to the dune core. If we compare the results of the top-conform model and of the base-conform model to the conceptual model, it is evident that the former grid building strategy provides far more geologically realistic results (closely resembling the conceptual model). The directions of major and minor sedimentary heterogeneity in the grid model are far better represented, both for the distribution and internal architecture of the sedimentary complexes.

Sedimentary body and surface modeling

Two contrasting approaches to model heterogeneity at a sedimentary body-scale could be to model the objects themselves (Cox et al 1994) or modelling the surfaces that bound them (Fischer et al 2007). The impact of the results that feed the conceptual model is obvious for modeling sedimentary bodies. The results provide qualitative and quantitative data that can be directly used to provide geological constraints to the body, such as body shape, orientation according to position, maximum thickness, width, etc. If sedimentary bodies are also modeled with an object-based approach (Pyrcz and Deutsch 2014), the results show that main body shapes in this deposit type are wedges and troughs, which are commonly modeled in most reservoir software. In a similar way, the results that feed the conceptual model provide bounding surface orientation, spacing, shape and hierarchy, also dependent on position within the bedform record. Some authors have considered bounding surface design as a central feature for the modelling workflow and even suggest well planning accordingly (Ciftci et al 2004). In simple dune related complexes, surface design complexity is far superior in the crest areas, and more predictable in flank areas. In some cases, bounding surfaces in deposits of this type are considered to have a baffling effect in fluid flow, especially when having a clear effect on cement distribution (Naides and Barrionuevo 2002), and therefore, considering surface distribution in heterogeneity modelling could have a significant impact.

Petrophysical modeling

Intra sedimentary body results that feed the conceptual model have a strong impact on how petrophysical properties in this reservoir type may be modeled. According to the conceptual model, cross-bedding dip-azimuth and dip angle can be predicted according to position within the preserved bedform. Since cross-stratification is the main source of heterogeneity within dune sedimentary bodies, if there is a considerable stratification type control on reservoir heterogeneity, 3D permeability should likely be conditioned with this data. In addition, intra-sedimentary body results provide information not only on the orientation and angle, but also on the abundance of stratification types throughout the sedimentary bodies. Stratification types (such as avalanche strata or wind-ripple lamination) conditions grain packing and therefore porosity and pore diameter. More closely packed wind-ripple lamination is far more abundant toward body bases, forming a discrete layer at the base or gradually increasing downwards, depending on body shape. This could therefore be an important heterogeneity to represent in a detailed model. Although this scale of heterogeneity is of considerable detail, petrophysical modeling could be conditioned considering these features using modeling trends, 3D permeability distribution, or using modules specifically designed to model this type of heterogeneities (Wen 2005).

POSSIBLE TENDENCIES IN FLUID FLOW INFLUENCED BY SEDIMENTARY HETEROGENEITY OF LINEAR BEDFORMS

Considering only sedimentary heterogeneity within the record of preserved eolian bedforms, it is suggested that two main sources of heterogeneity are likely to impact fluid flow. These are heterogeneity from sedimentary bodies and their bounding surfaces and heterogeneity from stratification orientation and stratification types within those sedimentary bodies. In other words, body-scale heterogeneity versus intra-body scale heterogeneity. While the former is of a larger scale (sedimentary body scale), the latter represents the vast majority if the rock volume within the record (intra-body scale). For a concentric style of architecture, two possible scenarios in which sedimentary architecture may impact fluid flow are presented, which are likely testable in the subsurface. These are represented by the same horizontal slice of a BEDFORMS geometrical model (Fig. 8) and likely maximum permeability orientations are suggested in each case. The first case represents body scale heterogeneity dominance on fluid flow, in which maximum permeability directions are subparallel to preserved bedform orientation. The second case represents intra-body scale dominance on fluid flow, in which max permeability directions are oblique to preserved bedform orientation.

CONCLUSIONS

The impact of the presented geological model for linear dunes of concentric architecture was evaluated, isolated for specific modeling tasks. Firstly, the possible use of the conceptual model's local scale features in the prediction of reservoir volume and geometry, as well as in hydraulic connectivity, was evaluated. Secondly, suggestions for reservoir zoning strategies were made from local, body and intra-body scale features of the conceptual model. The possibility of isolating intervals of specific preservation conditions, and/or sedimentary complexes, is highlighted at this point. Thirdly, the impact of the conceptual model in geocellular modeling

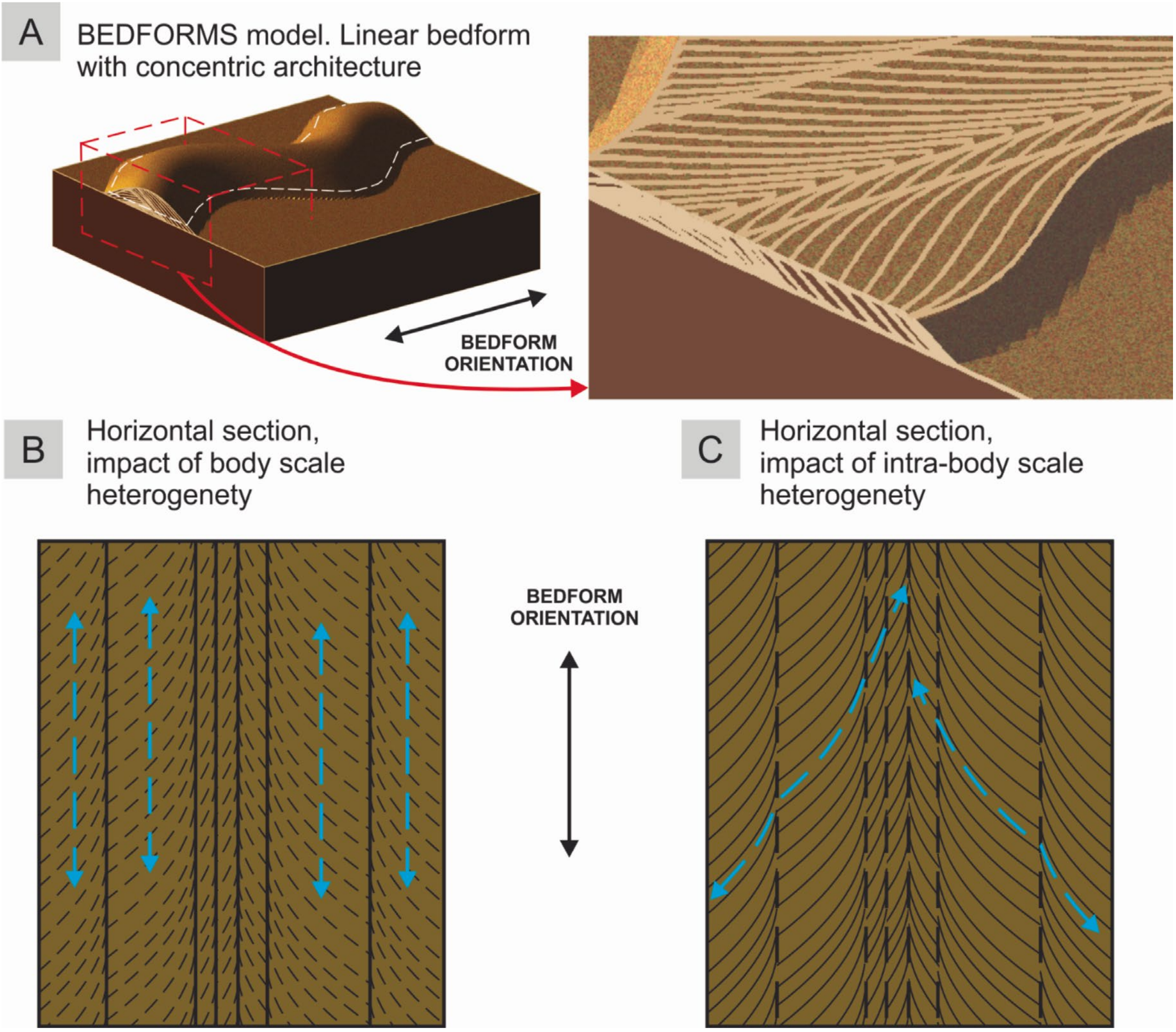

Figure 8. Possible effects of the sedimentary heterogeneity characteristic of a linear dune of concentric architecture upon maximum permeability directions. A) Detail of bedforms model used as reference (Arguello Scotti, 2017). B) Idealized scheme of a horizontal section of the bedform in which the bounding surfaces (body scale heterogeneities) have a dominant effect on maximum permeability direction (blue dashed lines). C) Idealized scheme of a horizontal section of the bedform in which the internal stratification (intra-body scale heterogeneities) have a dominant effect on maximum permeability direction.

tasks was evaluated, analyzing how the sedimentary heterogeneity of body and intra-body scale may be represented at grid construction, sedimentary body and surface modelling, and petrophysical modelling. Finally, maximum expected permeability directions in this type of architecture is suggested. Therefore, the possible implications of the conceptual outcrop model are explored in detail. As these strategies are suggested merely from achieving a more realistic model of geological heterogeneity, it is expected that in the future, the hypothesis provided in this study may be tested in actual subsurface scenarios, calculating their quantitative impact in static and dynamic models.

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