Data Collection, Interpretation, and Geologic Modeling of Outcrop: Cerro La Molata, Cabo de Gata, Spain*

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Abstract

Beginning geologic modeling students are taught early in their curriculum that geologic modeling software does not know anything about geology. In most cases, it is very likely that the final geomodel will not be useful unless the modeler has enforced geologic concepts via controlled horizon gridding, hierarchical property dependencies, intelligently selected dialog settings, and geologically reasonable conditioning methods.

This paper describes building an outcrop-based geomodel, including the preparation of LiDAR data for interpretation and horizon correlation between described sections in geomodeling software, creating time-equivalent model layers, use of reconstructed elevation pinning points to define paleobathymetry, and the geospatial analysis of depofacies distribution.We present the use of LiDAR outcrop scanning data to produce a photorealistic interpretable virtual outcrop, techniques to constrain extrapolation of horizon picks away from the outcrop face, and methods of enforcing paleobathymetric controls on depofacies distribution within time-equivalent model layers. We discuss the importance of maintaining comparability of flow simulation results between analog models to understand the separate effects of deposition, diagenesis, and deformation on fluid flow in carbonates. This work was part of the ExxonMobil-sponsored Fundamental Controls on Flow in Carbonates academic alliance.

Preparation of LiDAR Data for Use in Geomodeling Software

LiDAR (**Li**ght **D**etection **A**nd **R**anging) is a laser-scanning tool that produces multi-million point datasets. Each laser shot scan point is output with X, Y, and Z coordinates. Some contractors are able to add to each point Red, Green, and Blue intensity indices taken from high-resolution digital cameras co-located with the laser scanning equipment (XYZRGB). As geologic outcrops are topologically complex features, it is generally impossible to image an entire outcrop from a single scanner tripod location. To get complete coverage of the surface, scan points from multiple tripod stations must be merged. This merged file, however, can contain several hundred million individual points, and almost all desktop computers are incapable of dealing with this immense file size. Therefore, the merged pointset is subdivided into square “patches” or “tiles”100 or 200 meters on a side, each of which contain no more than 40 million points. Since many locations on the outcrop are visible to more than one scanning station, a large number of the scan points are redundant. In our case, filtering was done to keep only one scan point within each 5cm cube in space around the outcrop. In some cases, even these filtered patches were too large for the visualization/interpretation software to handle, so random decimation was applied to further reduce files to manageable sizes. These filtered datasets were exported as text files and imported into the geologic modeling software as pointsets with color attributes.

Producing a Photorealistic Interpretable Virtual Outcrop

A “Virtual Outcrop Model” (VOM) is a 3D digital representation of the outcrop. There are several formats of VOMs, including Virtual Reality Markup Language (VRML) and XYZRGB pointclouds. VRML is a triangular meshed surface optionally draped with high-resolution photographs, and these are very photorealistic if prepared with settings that capture fine topologic detail. Our intent is to perform geologic interpretation on the VOM, but only a few specialized software packages are available that allow digitization on VRML meshes. Unfortunately, these specialized tools are not designed to produce geocellular models, so data export-import is required between the VRML visualization/interpretation software and the geomodeling software. Geologic modeling packages are more easily available, but these do not generally allow the display of the VRML format VOMs. They do, however, support the display of point clouds. Therefore, in order to use geologic modeling software we imported decimated “patch” pointclouds and applied a 256-color palette for visualization in 3D (see Figure 1 upper). Digital elevation models (DEMs) were constructed for every patch, along with a synthetic “satellite view” orthophoto constructed from an orthographic straight-down 4 megapixel screen capture of the colored LiDAR pointcloud. When the DEM is draped with the synthetic orthophoto, a reasonable representation of the outcrop is created (see Figure 1 lower). Topographic overhangs are not portrayed correctly in these DEMs, nor are vertical faces. Though not entirely realistic, the DEMs can be used to navigate through the VOM to a desired outcrop location; then the DEM is removed from view, and the detailed LiDAR point cloud data is displayed in its place. Although cumbersome, this strategy worked very well for our purposes of stratigraphic interpretation and geocellular model construction.

Interpretation and Horizon Correlation between Described Sections Using LiDAR

The significant stratigraphic horizons are easily distinguished in the VOM. Interpreting the horizon correlations between the described sections is virtually equivalent to walking the beds along the outcrop from transect to transect, similar in most respects to drawing interpretations on a photopan of the outcrop, but with the added advantage of zooming and changing perspective as needed.

Information about depofacies at different locations should be captured from measured stratigraphic sections and geologic field mapping. These data can be supplemented with digitized facies interpretation on the VOM. If such interpretations were being made on a paper photopan, different colored pencils would be used to shade the photopan to indicate the presence of the various facies. In the 3D VOM, points that are tagged with the facies codes can be digitized onto the outcrop surface (see Figure 2 upper). Geologic mapping could be done on tablet laptop computers in the field by immediate digitization of facies descriptions on the VOM.

These tagged points can be combined with the facies descriptions in the described sections and "upscaled" into the geocellular framework (see Figure 2 lower). These upscaled cells remain unchanged during the subsequent property modeling steps. They serve as seed points for extrapolation of the facies model property and are also vital to the development of geospatial statistics and conditioning, such as facies probabilities as a function of paleo water depth.

Techniques to Constrain Extrapolation of Horizon Picks Away from the Outcrop Face

The extrapolation of stratigraphic horizon elevations away from outcrop picks can result in geologically impossible geometries. This problem arises when the control data are not widely distributed across the model region, and is especially severe when data occur only in a relatively small region of the model area. This is exactly the case in our study area because many of our horizons crop out on opposite sides of the La Molata ridge, and are separated by only a few hundred meters or less. Without intervention, small differences in elevation are extrapolated unreasonably by the available gridding algorithms, resulting in surfaces that crosscut incorrectly and bear little resemblance to the conformable stratigraphy of our conceptual model.

Two strategies were used to mitigate this. The first strategy involves the creation of supplemental elevation points that are optimized to fit the digitized horizon interpretation points and also to conform to an idealized surface geometry, which in this study are progradational lobes that are semicircular in map view and sigmoidal in cross section. The second strategy is called the Isochore Addition Method, and works by mapping inter-bed thicknesses, not elevations. We have observed that lateral changes in interval thickness are more predictable than lateral changes in elevation, especially in regions affected by structuring. This technique requires at least one reference horizon surface to be gridded in elevation. Usually an originally near-horizontal flooding surface is chosen for this role. Then all subsequent elevation surfaces are constructed by adding (or subtracting) interval isochores to the existing reference horizon or another horizon's previously constructed elevation grid.

Creating Time-Equivalent Model Layers

The correct orientation of geocellular model layers is important because most geostatistical modeling algorithms work on the assumption that layers represent geologic timelines. Modeling software packages offer a choice of only four layering options, three of which cannot adequately orient the layers in the prograding clinoforms present in this study area. The inadequate layering options are: (1) layering parallel to the zone top, (2) parallel to the zone base, or (3) creating proportional layers in which a fixed number of layers pinch and swell to fill the zone. Since these three methods conform to zone top and/or zone base dip changes that do not exist in the interior of the zones, each of these options produces layer orientations that are discordant to the beds visible on the VOM surface within the zones.

The one remaining option involves creating a layering-guide surface approximately in the center of each zone that visually aligns with bedding in the VOM, and then constructing the overlying and underlying model layers upward and downward parallel to that guide. This makes layers that are independent of zone boundaries that onlap the base and are truncated at the top. This layering is not ideal, but it is the best that can be achieved with the layering methods available. Finer subdivisions of the stratigraphy would allow more accurate orientation of the layers, but at the cost of significant additional effort.

Use of Elevation Pinning Points to Define Paleobathymetry within Time-Equivalent Model Layers

As every model layer intentionally represents a single fine time-stratigraphic unit without much internal facies migration, it follows that the paleo sea level during each layer's time of deposition was uniform across the study area. Some facies have known preferred water depths, and it is simple to assign a paleo-sea-level elevation to that observation's layer such that the observed facies occurs in the correct water depth. Associating a series of such key "pinning point" elevations with model layers (Figure 3) creates a piecewise linear lookup function that allows interpolation of paleo sea level onto every model layer, even onto those layers lacking diagnostic water depth facies observations. After the paleo-sea-level elevation datum of each layer is populated, we simply subtract each cell's elevation from that datum to create a paleo-water-depth property.

Geospatial Analysis of Depofacies Distribution and Enforcing Paleobathymetric Controls on Depofacies Distribution

There is a predictable pattern of facies associated with paleo-water depth that is supported by preserved paleotopography on clinoforms. For example, reef organisms are much more likely to be found in high-energy shallow water settings, whereas wackestones are more probable in quiescent deeper water settings. The paleo-water-depth property in combination with the described section facies interpretations and the interpreted facies points on the VOM allow the definition of a facies probability function with paleo-water depth as the independent variable (Figure 4). This probability function is then used to guide the extrapolation of facies throughout the geocellular model. A geologic model populated with attention to such probabilistic conditioning (Figure 5) is far superior to one that has only described data as conditioning.

Maintaining Comparability of Flow Simulation Results between Analog Models to Understand the Separate Effects of Deposition, Diagenesis, and Deformation on Fluid Flow in Carbonates

The geocellular model will be used in flow simulation experiments to characterize the effects of reservoir architecture, diagenesis, fluid types, recovery mechanisms, and well configurations. Further, we need the conclusions from this study to be comparable to similar flow studies done on other geologic models built from other reservoir-analog outcrops. In order to be sure the simulation performance differences between models are not the result of arbitrary choices of porosity and permeability, we need to "hold constant" as much as possible the porosity and permeability values used. By standardizing reservoir quality assignments, comparisons between these models will highlight differences due only to architecture, facies distributions, and geomodeling options.

To meet this objective, we have provided the members of our research alliance with a "Standard Property Calculator" (SPC) tool that accepts an objective rock description as input and produces as output five summary statistics that allow the population of porosity and permeability using typical geomodeling process dialogues. These statistics are Average Porosity, Standard Deviation of Porosity, Slope of Poro-Perm Transform, Intercept of Poro-Perm Transform, and Standard Deviation of Permeability Scatter with respect to the Poro-Perm Transform. Using this tool, we ensure that rocks with identical descriptions will get identical rock quality assignments, while still accommodating the natural variations in sediments between study areas in a consistent way.

The algorithm behind the SPC tool was calibrated using multivariate linear regression on a database consisting of core plug porosity and permeability plus detailed rock description elements coded by abundance. The approach is too simplistic to be used for actual hydrocarbon assets, but the SPC does produce reasonable point clouds that display the relative shifts in position on the poro-perm crossplot that carbonate experts expect to see when various parameters like cementation, pore size, matrix sorting, and isolated moldic fabrics are introduced.

Conclusion

Seven scenarios of diagenetic overprint have been built including: (1) with and (2) without dolomitization, (3) with and (4) without water table calcite cementation, and another that (5) combines variable dolomitization and water table cementation. A sixth scenario using (6) actual core plug data from the La Molata outcrop was also built, and serves to highlight the differences between our standardized rock property assignments and reality. A final scenario used a (7) rank transform to incorporate all of the diagenetic effects of our sixth model into a seventh model with the poro-perm characteristics of the outcrop core data.

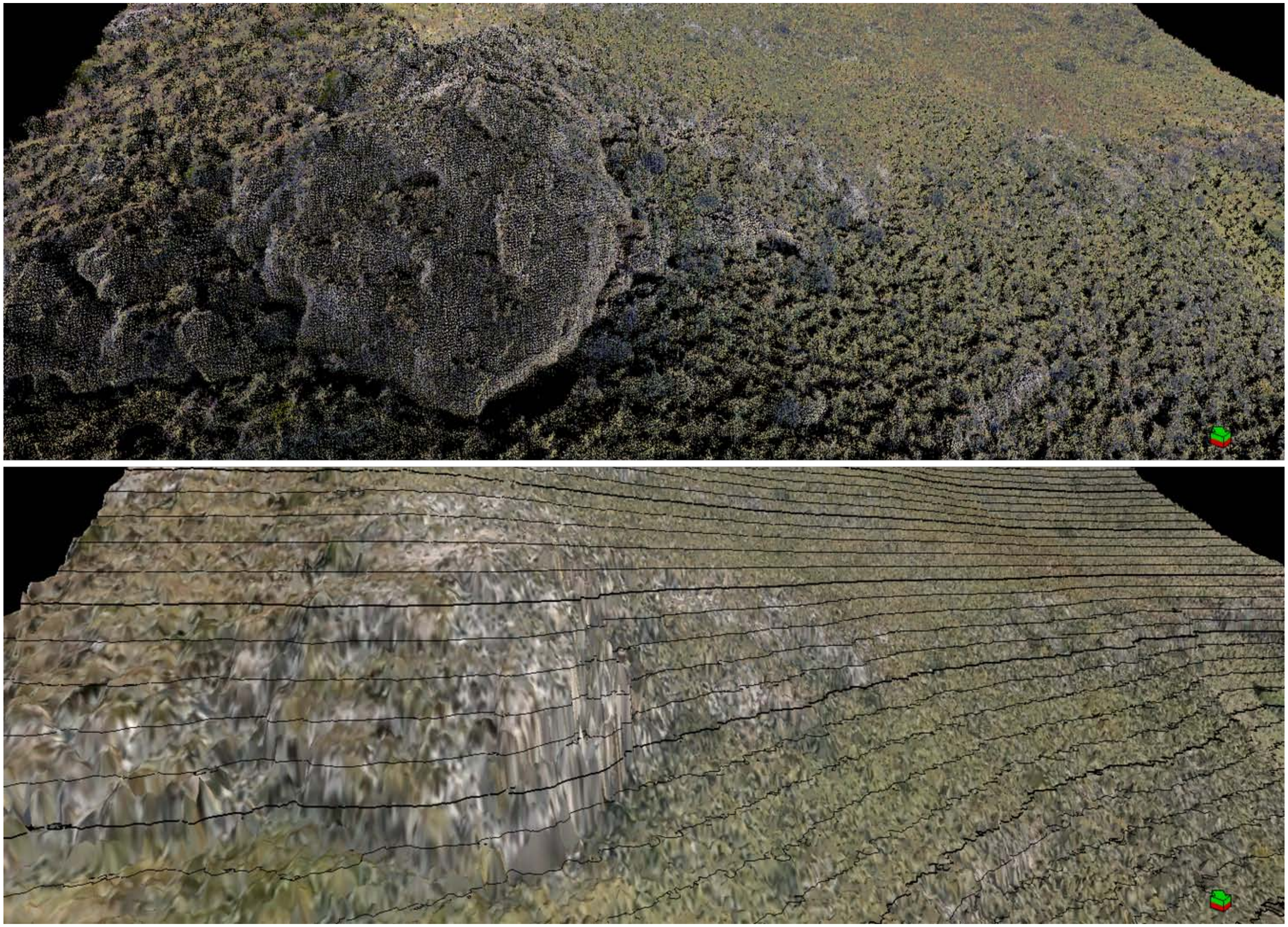

Figure 1. LiDAR shotpoints from all tripod positions are concatenated together and divided into 200 x 200 meter "patches" so that the modeling software can display the pointclouds without overloading the system memory. In some patches, the shotpoints had to be filtered to reduce the number of points. The single 200 x 200 meter patch shown in the upper image has 5.1 million LiDAR shotpoints. Note the black areas with no points in them. These are locations that were shadowed from the laser by foreground objects. The lower image shows a high-resolution Digital Elevation Model (25 cm grid node spacing) made from the LiDAR point elevations and draped with a synthetic orthophoto derived from the LiDAR point colors. Some loss of surface detail occurs because the DEM cannot portray overhang topology or vertical faces. It is also possible to drape the DEM with geologic maps instead of synthetic orthophotos (not shown), and we found this to be an important supplemental data source during the tagging of facies interpretations on the VOM. Contours are 1 meter. Vertical exaggeration = 1.0

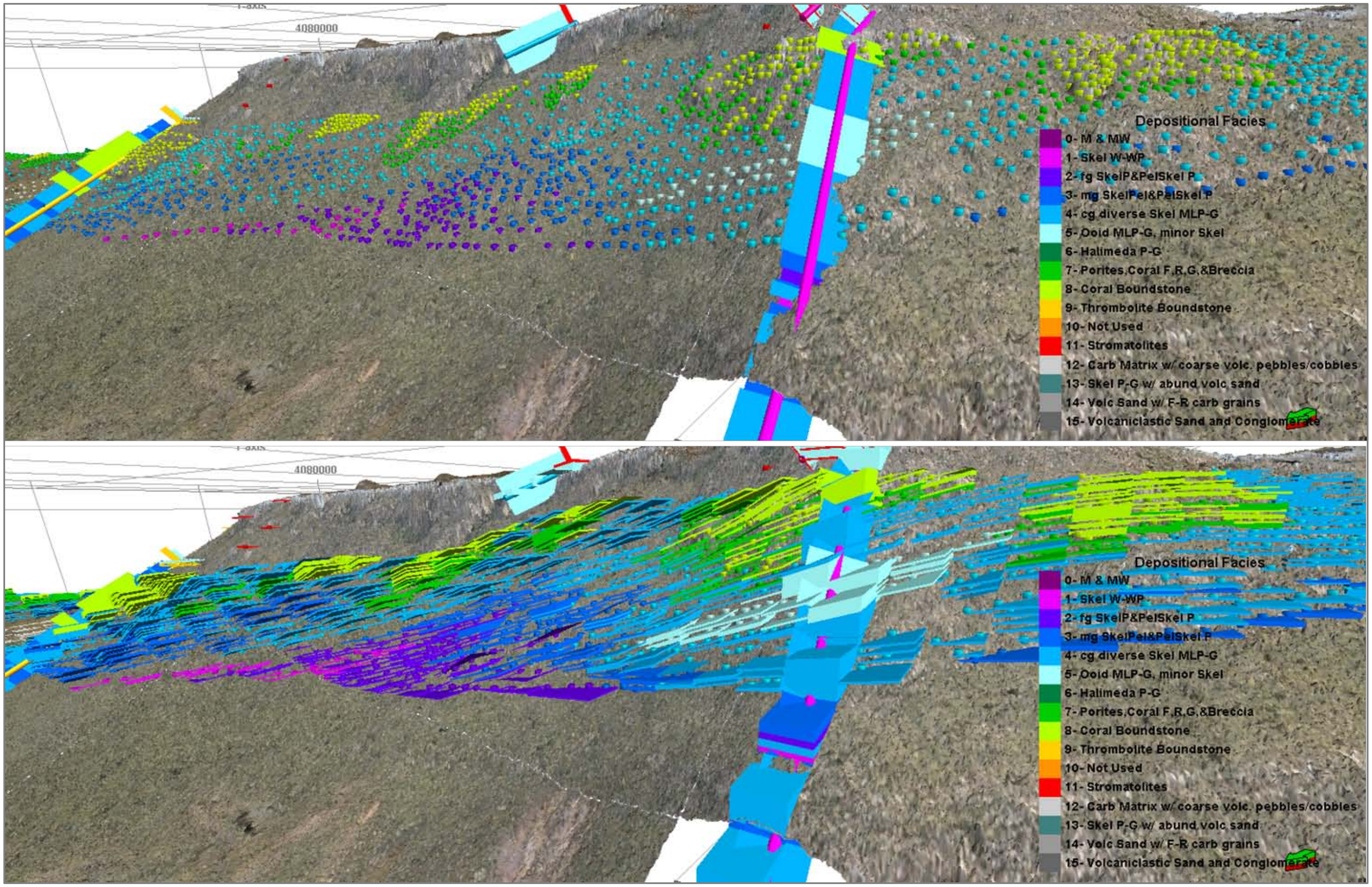

Figure 2. Depofacies observations in described sections were supplemented by digitizing points across the Digital Outcrop Model draped with an orthophoto (upper image) or a detailed geologic map of facies (not shown). These were combined with described sections (colored ribbons) and upscaled into the geocellular framework, creating “hard” cell property data that remained unchanged through the subsequent geostatistical modeling process (lower image). Having a large quantity of facies interpretation data was important to developing robust spatial statistics, such as relating facies probabilities to position on the depositional profile.

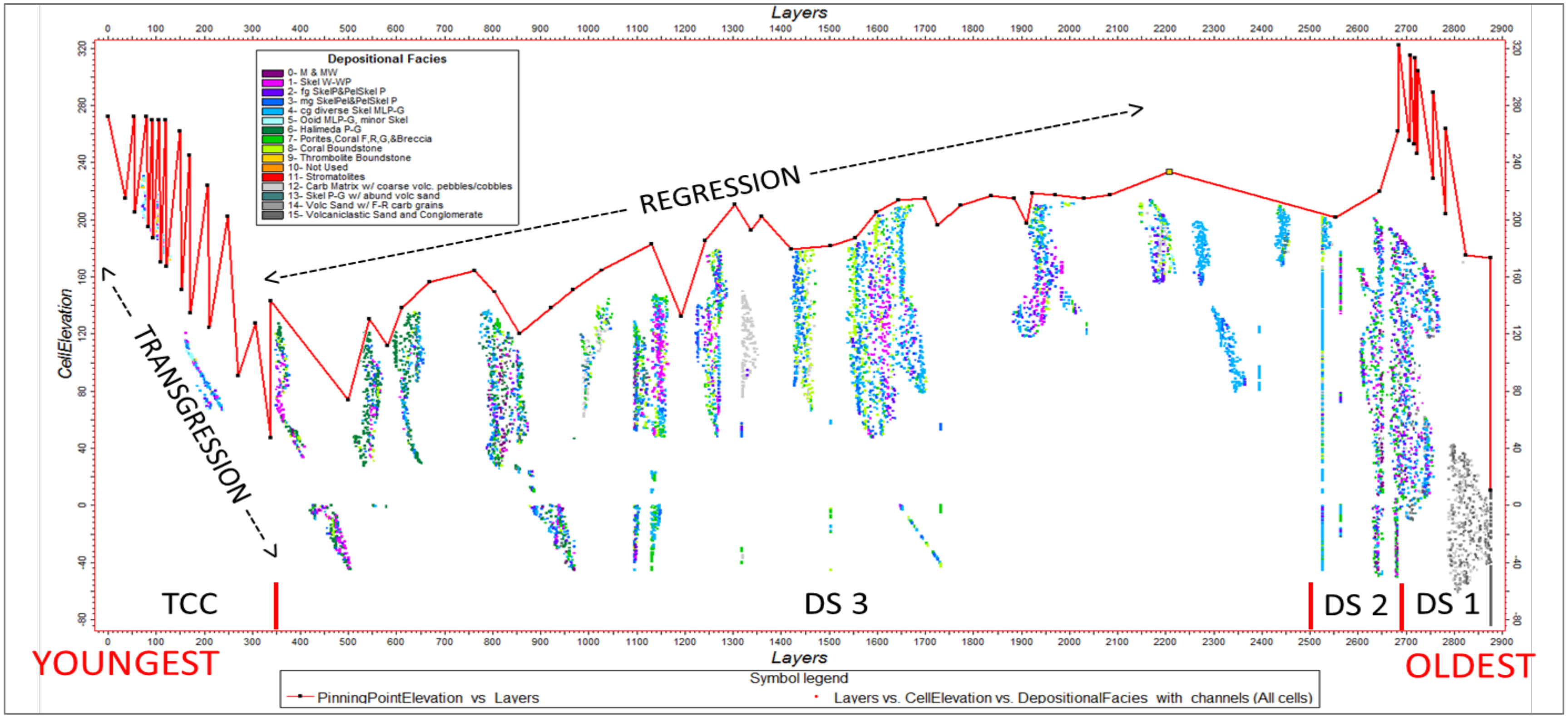

Figure 3. The relationship between paleo-sea level and model layer number can be visualized as a piecewise linear function with layer number as the independent variable (red line). The function is created such that shallow water facies (e.g. light green coral = boundstone) have a sea-level datum located a relatively short distance above them, whereas deeper water facies (e.g. pink = wackestones) have paleo sea-level datums a greater distance above them.

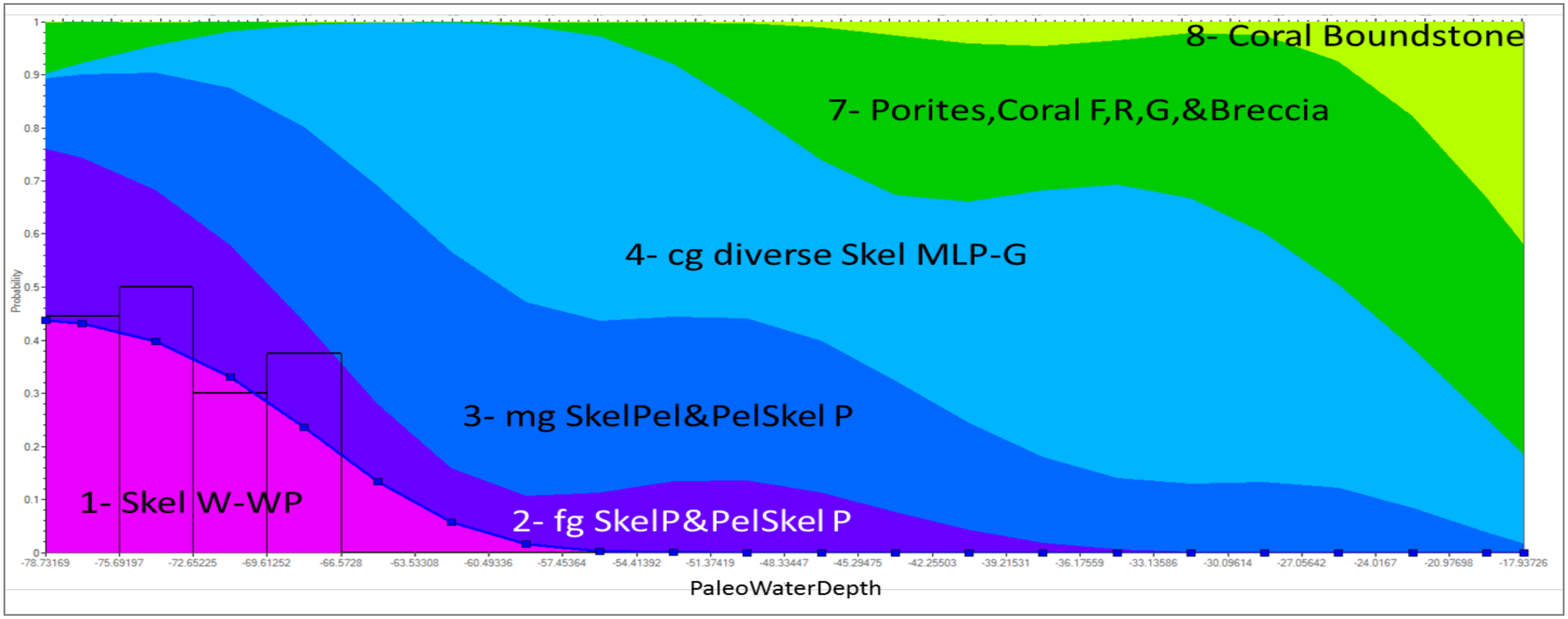

Figure 4. The probability of facies occurrence (vertical axis) can be related to Paleo Water Depth (horizontal axis). The height of the colored bands represents the probability of the facies at that water depth, based on observed occurrences of facies descriptions at various depths. This relationship can be used to populate geologic models realistically.

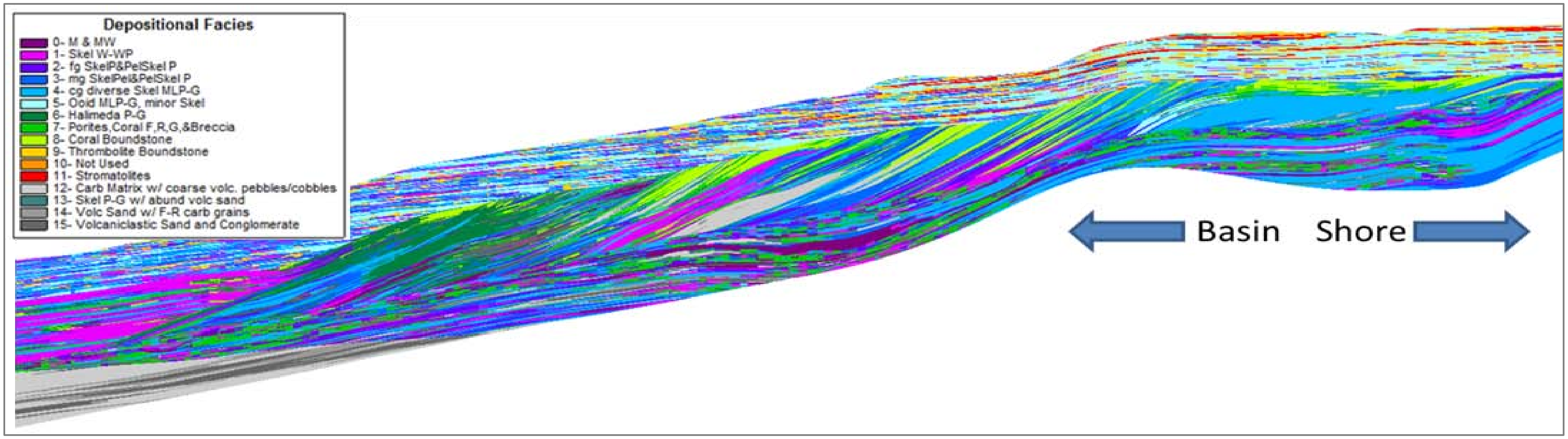

Figure 5. Cross section through La Molata geologic model. Note the predictable progression of facies from high-energy facies in the shallowest positions within layers to fine-grained low-energy facies in basinal positions. This pattern was enforced using the Truncated Gaussian Simulation (TGSIM) algorithm in combination with the water depth/facies probability relationship.