Multidisciplinary Data Integration for 3D Geological Outcrop Characterization, Jackfork Group, Hollywood Quarry, Arkansas*

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Abstract

The Hollywood Quarry, located in Clark County (near to Hollywood, AR), Arkansas, has been studied using many techniques in order to characterize its stratigraphy, structural deformation and general geological features. The quarry exposes deepwater sediments of the Jackfork Group (Pennsylvanian) often utilized by petroleum companies as a potential 3D deepwater outcrop analog used to evaluate performance of this type of reservoir. The outcrop allowed the study of classic features of a deepwater reservoir from a structural point of view (faults and folds), and from a stratigraphic point of view (characteristics of sheet and channel sandstones).

The main goal was to build a refined 3D geological model of the outcrop based on a previous model built from outcrop and subsurface gamma ray logs, facies descriptions, and porosity datasets (Goyeneche et al., 2005) and integrating new 2D near-surface seismic reflection sections and Ground Penetrating Radar (GPR) profiles, outcrop images (photomosaics), GPS data and stratigraphic columns acquired from newly exposed quarry walls.

The newly exposed quarry walls are a result of recent blasting activity in the quarry. These exposures, never before seen, made it possible to compare our geological interpretation of the seismic and GPR data acquired prior to removal of the rock with the true outcrop geology revealed in the new exposures. These results allowed us to improve the characterization of the structural and stratigraphic geometries and, in particular, their response to the remote sensing methods. The correlations between the true outcrop

geology and seismic/GPR data interpretation were good, thus demonstrating the value of using geophysical techniques for 3D outcrop characterization of reservoir analogs.

Introduction

The present work on deepwater deposits is based on observations, measurements, and interpretations of upper Jackfork outcrops in southwest-central Arkansas (Figure 1), and can be used as a guide for interpreting the subsurface Jackfork Group in eastern Oklahoma (Slatt et al., 2003). (Figure 2)

The natural laboratory of Hollywood Quarry has been studied using different techniques in order to characterize its stratigraphy, deformation and general geological features. (Figure 3 and Figure 4) Stratigraphic sections, fracture analysis, borehole image logging (FMI), outcrop gamma- ray (GR), sequential photography of quarry walls and Laser Imaging Detection and Ranging (LiDAR) were some of the techniques used in the past by Goyeneche et al 2005 to characterize the quarry. Liceras (2010) characterized and modeled the stratigraphy and structures of the quarry in detail. The first 3D GPR acquisition in Hollywood quarry was made by Peterson (1999). This research was continued by Hinestrosa (2001) who reprocessed the data of GPR with the purpose of studying the structural and stratigraphic features.

An analog example of deepwater characterization using GPR was developed in the Lewis Shale located in Wyoming (Slatt et al., 2007). The profiles obtained behind the wall shows turbidite channels and sedimentary structures. Also, lateral accretion packages were observed and on-lap and down-lap patterns. This study described the utility of GPR in defining the geometry of deepwater turbidite channels.

Gregg (2006) shows the acquisition and processing of multi-line high-resolution 2D seismic in the quarry. The purpose of this study was to compare two methods of shallow seismic data processing: synthesis of plane waves (PWS) and stacked by common midpoint or “CMP”. Thanks to this work, acquisition parameters were revised and the results obtained indicated that coherent noise might occur during the acquisition. The 2D seismic surveys are characterized by the presence of coherent destructive noise, which is not easy to remove with a basic sequence of processing.

Fortunately, with advances in technology, new geophysical data sets have been acquired in the area, including 2D seismic lines and Ground Penetrating Radar (GPR) profiles used in the present study. These two new data sets give the opportunity to understand the distribution of the architectural elements (in this case submarine channels) beyond the quarry’s walls. The purpose of these two geophysical techniques was to image two different geological features: stratigraphic distribution and structural complexity using GPR and near surface seismic survey respectively, in order to build a refined 3D geological model of a part of the quarry.

Geologic Setting

The Hollywood Quarry is located in the Ouachita uplift in southwest Arkansas (Figure 5). This is a three-dimensional excavation, which exposes the stratigraphy and structure of part of the Jackfork Group. Studies in this quarry provide an analog example of deep marine reservoirs present in the Gulf of Mexico (Jordan et al.1993, Slatt et al 1994; Goyeneche et al, 2007).

Hollywood Quarry is 400*200*23 m in dimension which exhibits deepwater deposits, sealing and non-sealing faults (extensional, thrust and strike-slip faults), folds, fractures and injectites. Hollywood Quarry has been documented sufficiently to build 3D geologic models for simple “reservoir” performance simulation (Jordan et al., 1991; Slatt, 2000). Goyeneche et al. (2007) and Liceras (2010) characterized and modeled the stratigraphy and structures of the quarry in detail. For a further overview of the Jackfork group, see Slatt et al., (2000).

Northeast

New stratigraphic characterization was made to the New East wall of Hollywood Quarry, which was blasted out few months ago (Figure 7). The new wall showed a lower interval composed of interbedded shale – sandstone sequence that varies toward a massive sandstone toward the top, the thickness of the whole section is 15 m. Shale rip up clasts, fractures and some matrix occur within the section. The general strike of the beds is N40°E with dips around 15° toward the west. Current marks and fracture planes are some of the additional data acquired.

West

The west wall of the quarry exposes 21 m of upper Jackfork strata that is laterally continuous from south to north over a distance of 380 m along the west wall. The beds dip 12-14° W; Goyeneche (2005) characterized two major sandstones on the west wall, interbedded with black shale. Several strike-slip faults are present on the west wall of the quarry (Figure 8).

South Wall

This wall is special because of the abundant geological structures that can be studied in detail, such as faults with gouge and an asymmetric anticline. The layers described on the southeast corner (Figure 6) have a dip of 79-85° in the southwest direction; the dip of these layers diminishes gradually toward the west to 37-40° and finally, in the southwest corner of the quarry the dip is 12-14°. The strikes of layers change from north-south to east-west. These patterns define a limb of an asymmetric anticline (Figure 9) (Goyeneche et al, 2007).

A measured section from the floor of the quarry to the top of the south wall was described by Althoff and Montiero, (2009).This section represents a marine sequence of channels that is marked by the presence of abundant soft sediment deformed beds and molds of brachiopods. The shale in the lower part includes fine-grained sand lenses and the largest sand body is eroded. Overlying the anterior body is sandstone with a very fine grain size fining upward to silty shale; the thickness of this interval is 0.7 m.

The increasing sand content stratigraphically above the previous intervals can represent the migration of the channel due to the meandering nature of the channel facies down-dip (Althoff et al, 2009). The section is composed of 1.4 m of massive sand, 1 m of black fissile shale, 3 m of massive sandstone and 2.5 m interval of interbedded interval of sandstones and shales.

Six different facies were identified on the walls of the quarry (Figure 10):

- Sand3: The sandstone3 is lenticular channelized pebbly sandstone, of brown to gray color. This deposit represents a channel fill sequence of amalgamated sandstone bodies.
- Sand/Shale1: This interval is composed of thinner-bedded, fine to medium-grained sandstone and interbedded black shale. This unit is interpreted as layered sheet sandstones, which were deposited over the channel fill (Slatt et al., 2000).
- Shale 2: Shale 2 is black, fissile, and fractured. This shale bed is continuous along the length of the west wall and is correlated to the south and east quarry walls. It has a high gamma-ray response.
- Sand 2: This facies is a fine to medium-grained sandstone. It has abundant mudstone clasts, carbonized plant fragments; soft sediment deformation and water escape structures.
- Shale 1: The shale 1 is thinly laminated with siltstone beds. It has a black color, is, fissile and has a high response on the GR log.
- Sand 1: The lower interval is an amalgamated sandstone, which is quartz cemented, and massive. Sedimentary structures include load and scour structures, parallel laminations, planar cross-beds, ripple lamination and fluid scrape structures

Methodology

During the past 30 years, interest in the use of seismic in acquisition of near surface geophysics has grown significantly. According to Clay (1990), since the 1920's the technique of seismic reflection was implemented on shallow subsurface exploration. This trend continues from 1980 with the development of computer technology, which allowed small businesses and educational institutions to access the seismic reflection technique that has only been used by oil exploration companies in the past. From this point forward new techniques in the reflection method have evolved, as well as improvements in instrumentation and better understanding of the problems presented during the acquisition of shallow seismic reflection. The studies of GPR in near surface geology allow us to complement the reservoir characterization and correlate field geology studies, well data and cores in an integrated study of the area, allowing the development of geological models of marine deepwater reservoirs (Slatt et al. 2003).

GPR and Seismic

The high-resolution near surface seismic reflection survey was acquired in 2010 in the south wall of the quarry to image an anticline; additionally, with the same orientation a GPR survey was acquired to compare the effectiveness of both techniques in the same strata. A second GPR survey was acquired in the northeast wall of the quarry to interpret the location and architecture of deepwater channels. Moreover, thanks to the recent blasting activity in the quarry it was possible to compare the geological interpretation of GPR data to the real geology exposed on newly blasted surfaces. Stratigraphic columns were measured for the new east wall to compare with the interpretation made using only GPR data.

Two GPR profiles were acquired along the northeast wall of the quarry using a pulse EKKO 100 TM system from Sensor & Software, Inc. The northeast GPR survey was acquired by Brito (2010); it consisted of two lines with N-S and NNW-SSE orientation respectively (20° of separation approximately). The length of the two lines was 74 m. Some of the acquisition parameters were: space between antennas was 1 m, step interval was 0.25 m, nominal frequency was 100 MHz, and time window was 320 nS and number of trace per point 400. The GPR profiles were processed with EKKO View Software by Brito (2010). The final GPR section was superimposed with a photomosaic of the new northeast wall, as shown on Figure 11.

The near surface reflection seismic line was acquired in the South wall of the quarry using a Geode seismograph. The geometry of the array was split-spread type with a 50-meter length. The space between each receiver was 0.5 m; the source used on the field was a sledgehammer striking an aluminum plate with a shot interval of 0.25 m. The seismic was processed using SeisUp software. The interpretation of the seismic section acquired is shown on Figure 12, a dipping reflector was interpreted and it corresponds with the top of the Sd-Sh1 interval. In addition, some reflectors were onlaping the dipping structure and with the help of the outcrop were determined to be sand bodies that had onlap terminations.

GPS Data

The location (x,y) and the elevation (z) coordinates of seismic and GPR profiles were recorded with the help of the GPS. The GPS unit was also used to map the new edge of the Northeast wall (Figure 13), which was recently blasted. The interval between each station was 20 feet and it was measured along the base of the wall. Forty-two stations were recorded. Moreover, the GR log, the measured sections and the photomosaics have GPS point locations also with the purpose of including them in the final model.

Outcrop Images

Lithological and structural interpretations of the outcrop images were made from several measured sections and from additional observations. This technique is particularly useful for bridging the substantial gap between seismic and individual well scales, particularly when outcrop images are placed into different computer software's and making the interpretation of them easier (Dueholm and Olsen, 1993). Bounding surfaces and faults can be highlighted and facies characteristics can be identified and their proportions measured (Slatt et al., 2001).

Gamma Ray Logs

A stratigraphic borehole was drilled and cored by Schlumberger-Chevron-Texaco in 1994 through Jackfork strata approximately 50 m behind the west wall, penetrating to a depth of 67 m. Since that time, quarry operations have excavated the west wall (Figure 6) so that the well casing now is exposed along the wall (Goyeneche et al, 2007). Two boreholes also were drilled 4 m apart and 250 m southeast of the east quarry wall. This wall is composed of highly fractured and faulted, shallow-dipping, massive sandstone that underlies the strata exposed along the west quarry wall. The first borehole cored 28 m of the sandstone that is exposed on the east quarry wall. The second borehole was drilled for 57 m and logged with Schlumberger's Formation MicroImager™ log (Slatt et al., 1994).

Outcrop gamma-ray logs were obtained in several of these locations using both a logging truck and a hand-held scintillometer (Slatt et al., 1992; Jordan et al., 1993; Slatt et al., 1994; Slatt et al., 1995; Goyeneche, 2005). Gamma log responses and rock properties were qualitatively correlated with stratigraphic characteristics of the quarry (Figure 8).

Facies Logs

Fifteen stratigraphic sections were measured. Outcrop gamma ray logs were obtained in several of these locations using a hand held scintillometer. Gamma log responses and rock properties were qualitatively correlated with stratigraphic characteristics of the quarry. Pseudo facies logs were created based on the GR response. An absolute number was assigned to each facies (0: Sandstone3, 1: Shaly/Sandstone, 2: Shale2, 3: Sandstone2, 4: Shale1, 5: Sandstone1) corresponding to the depth of occurrence (Figure 8)

3D Geological Model Construction

The well tops and dips azimuth data were from previous studies on the area. Based on Goyeneche´s (2005) model the data was imported into the PetrelTM software to construct the 3D geological model (Amorocho et al 2009).

Twelve well locations were used to build the model; those wells have pseudo-facies logs, gamma ray information, porosity and permeability (Figure 14).

1. Surfaces creation: In order to build the model, it was necessary to create six surfaces based on the information of the well tops (Figure 15). First, a polygon of the whole quarry was defined. The interpolation algorithm used a 25x25 feet grid increment to create the surfaces. Seven surfaces were generated: unconformity (erosional surface of the actual position of the quarry top), sand/shale1, shale2, sand2, shale1, sand1 and the base contact.
2. Fault Modeling: Fault planes were created using a fault plane (Figure 16) map; the faults traces were drawn based on the interpretation of the fieldwork. Eleven faults were modeled
3. The pillar gridding: This step was made after the fault modeling using a 25x25 feet cell size. Creating 107x129x20 cells that made 276060 cells (Figure 16).
4. Horizons: The first step to create the model is the generation of the 2D surfaces (Figure 17). All the surfaces were created taking into account the different boundaries (unconformities, erosional, conformable, etc.) In addition, the top and the base of the quarry were defined. Some of the facies identified were described as conformable boundaries to avoid truncation between the horizons.

5. Zones and Layering: Six zones were generated automatically after the horizon creation. Layering used was proportional for all intervals (Figure 18). Proportional layering consists of a constant number of cell layers at every pillar of the grid.
6. Property Modeling: When modeling different properties, a 3D area is generating by the grid. Each grid cell has a single value for each property; well data must be scaled up. Facies modeling (Figure 19) is the distribution of the facies information along the grid and the petrophysical modeling consists of filling the cells of the grid with the information available from the wells (GR, porosity and permeability), in order to make the model more realistic (Figure 20).

Results

The model is used to interpret the East-West deposition direction trend of the Jackfork Group in the quarry. The strata are dipping 12° to the west and can be observed in Figure 18. This direction is congruent with the regional geology depositional trend (Figure 4). The 12 degrees is structural dip, though; not related to depositional trend.

On the South wall, the structural map shows that the dipping of the layers increases southward. The geological model also shows the steeper dip to the south. Figure 22 shows how the layers of the model intersect a photomosaic from the wall with increasing dipping south.

Figure 21 shows the correlation of facies model wall with a superimposed image of the migrated section. The data used for model development are based on facies pseudo logs, gamma ray, permeability and porosity. These tops are purely stratigraphic. The layers of different facies in the model agree with the reflectors present on the seismic; the image is displayed from the north. An image with a rear view is shown in Figure 16. Reflectors correlate very well with the lithology of the quarry. This indicates that the shallow seismic reflection survey was able to illuminate layers of strata. This is a high-resolution seismic method because of the details obtained from it. Furthermore, on the West wall the results obtained from the 3D model were correlated with an outcrop picture of the wall (Figure 22). A good correlation was obtained between the layering of the beds and the surfaces created with the model (Figure 23).

Studies behind outcrop using GPR analysis shows that the channel fill interpreted by Brito (2010) cannot be observed on the stratigraphy exposed along the west wall. The dipping of the beds is 12° W, so it is inferred that the channel is located beneath the floor of the quarry (Figure 24).

From the petrophysical model, it can be inferred that the areas with the same porosity and permeability values correspond with the sand intervals, while in the shales the values can vary (Figure 20). The model shows a good approximation to the outcrop data. The results obtained allow improving the reservoir characterization of the Jackfork Group.

Discussion

All the available information is based on well data points. Each well has information about different attributes facies, GR, porosity, etc. This data was extrapolated using a mathematical algorithm. However, lateral variation of facies in this type of reservoir is very common; therefore, the extrapolation algorithm might have errors during the computing of the facies Because of this problem, geophysical methods play an important role in providing better detail.

On the other hand, in order to cover 3D area with a higher precision, near surface methods were used (GPR-Seismic) to correlate the results obtained by the geological model. Advantages to building geological models based on outcrop data:

- This research allows the geoscientists to find an easy way to develop a geological model for a specific type of reservoir.
- The geological and geophysical methods used on this work are accessible and easy to use.
- Hollywood Quarry is an excellent analog 3D model of a real deepwater oil field.

Summary

- The outcrop allowed the study of classic features of a deepwater reservoir from a structural point of view (faults and folds), and from a stratigraphic point of view (characteristics of sheet and channel sandstones). They provide a powerful tool for training geoscientists as well as reservoir engineers in reservoir behavior. Outcrop “reservoir” modeling is a very valuable tool for judging the importance and influence of various reservoir features such as shales, faults and reservoir structure on flow.
- 3D geological models are very useful as a prediction tool, in areas were the information is limited.
- Production plans can also be made based on the results obtained by the geological model.
- Several sub-seismic scale faults, a fold, and lateral accretion package have been identified, making it a structurally complex rock volume. This kind of complexity is very likely to occur in real reservoirs.
- The correlations between the true outcrop geology and seismic/GPR data interpretation were good, thus demonstrating the value of using geophysical techniques for 3D outcrop characterization of reservoir analogs.

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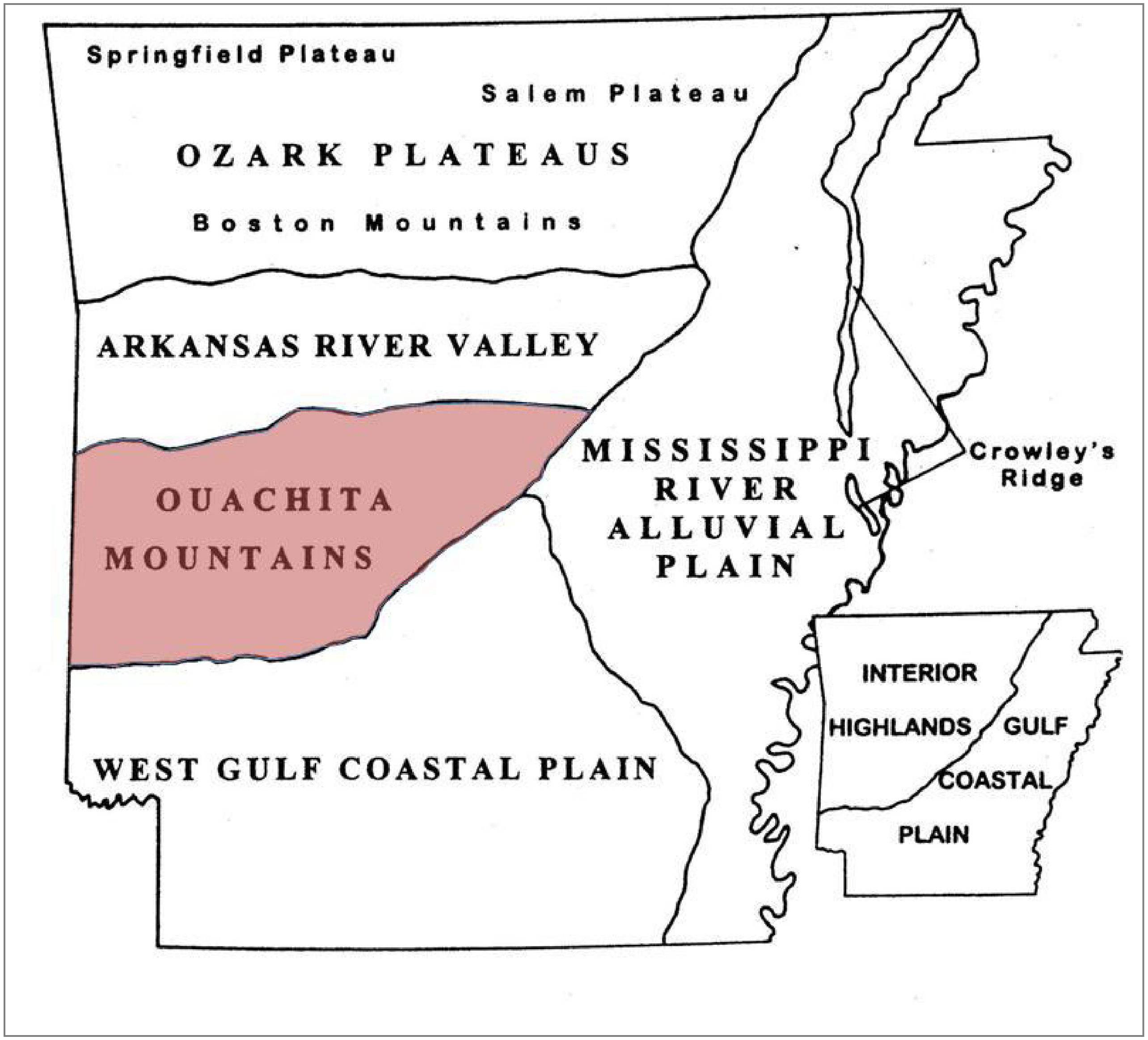

Figure 1. Map of the physiographic provinces of the state of Arkansas, in red is highlighted the province of the Ouachita Mountains, where is located the study area. (Modified from Arkansas Geological Survey).

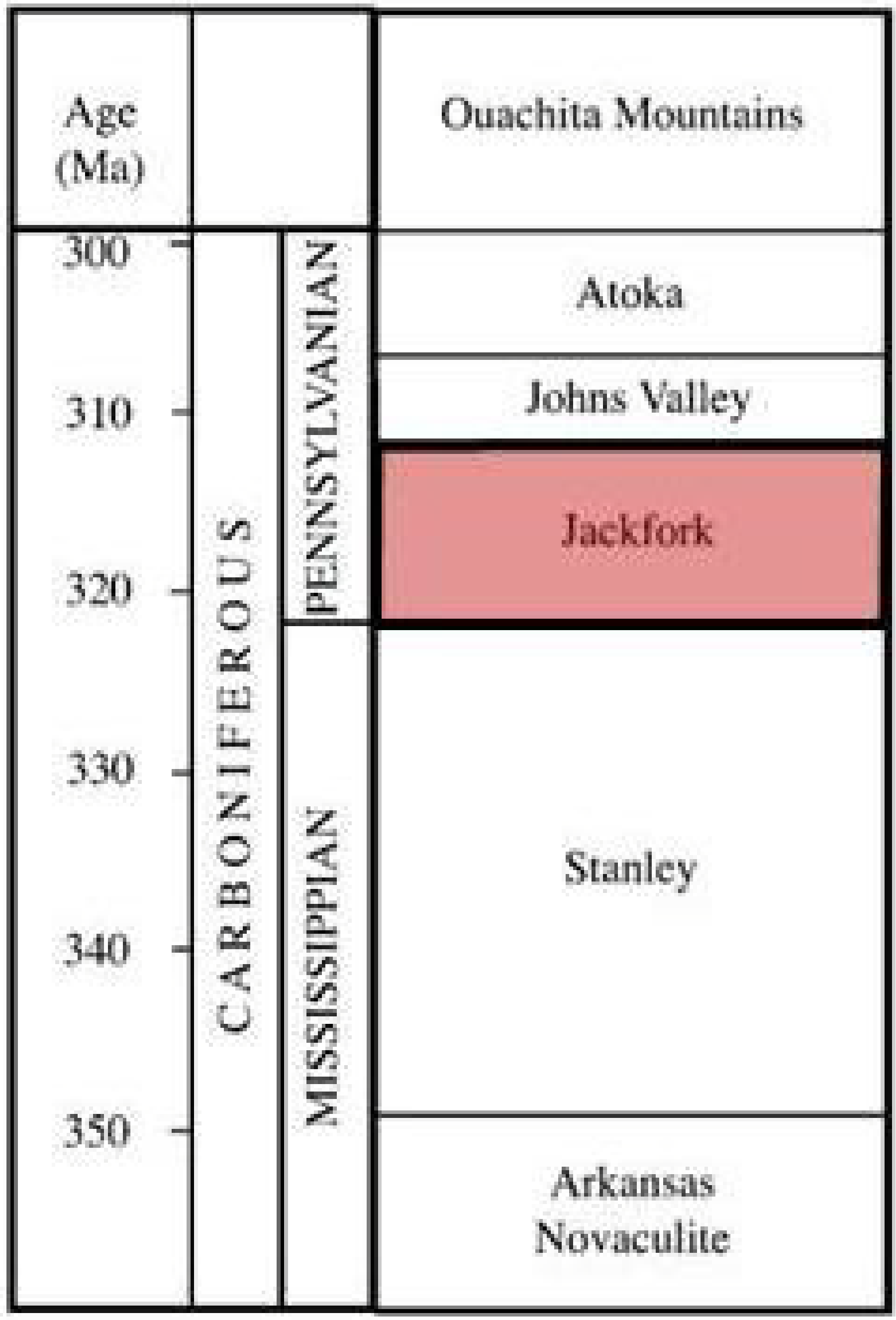

Figure 2. Chronostratigraphic chart of the Ouachita Mountains (modified from Ethington et al., 1989).

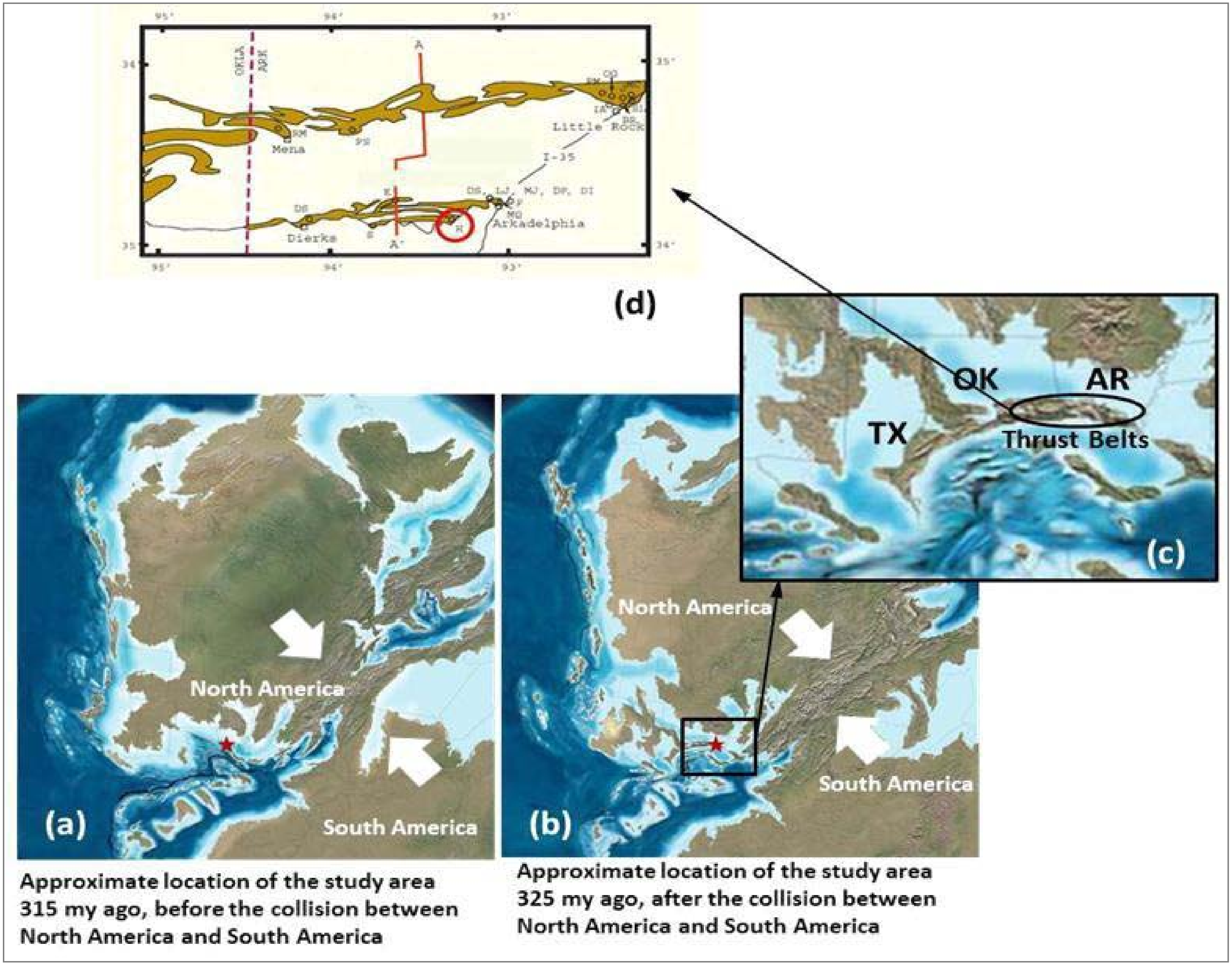

Figure 3. History of the paleotopography of the basin. (Modified from Slatt, 2010).

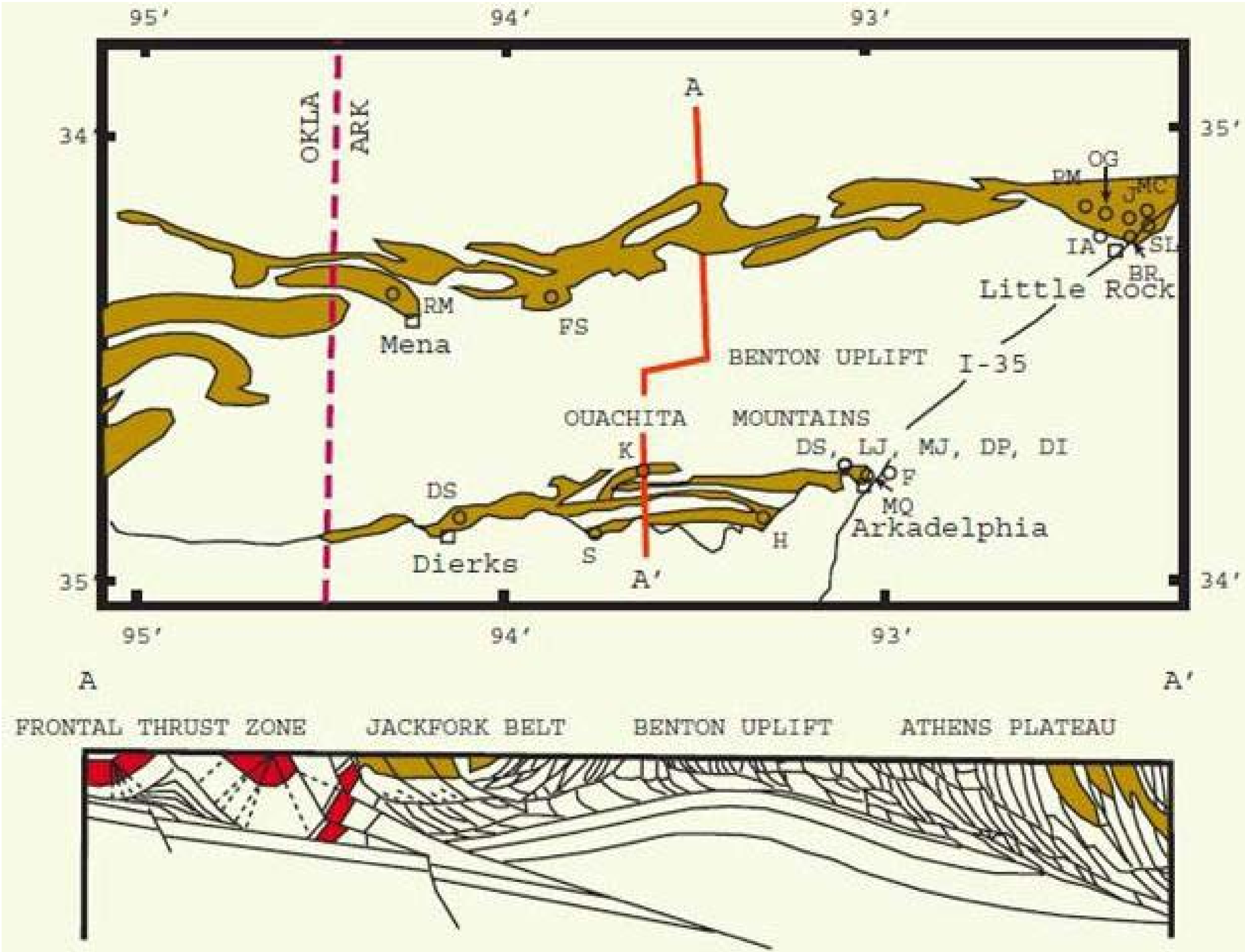

Figure 4. Simplified geologic map showing the east-west trend of the Jackfork Group (orange) along the northerly Ouachita and southerly Athens Plateau belts. Complex structure is shown along a north-south (A-A') cross section. H= Hollywood Quarry. (Image courtesy of Slatt et al, 2000).

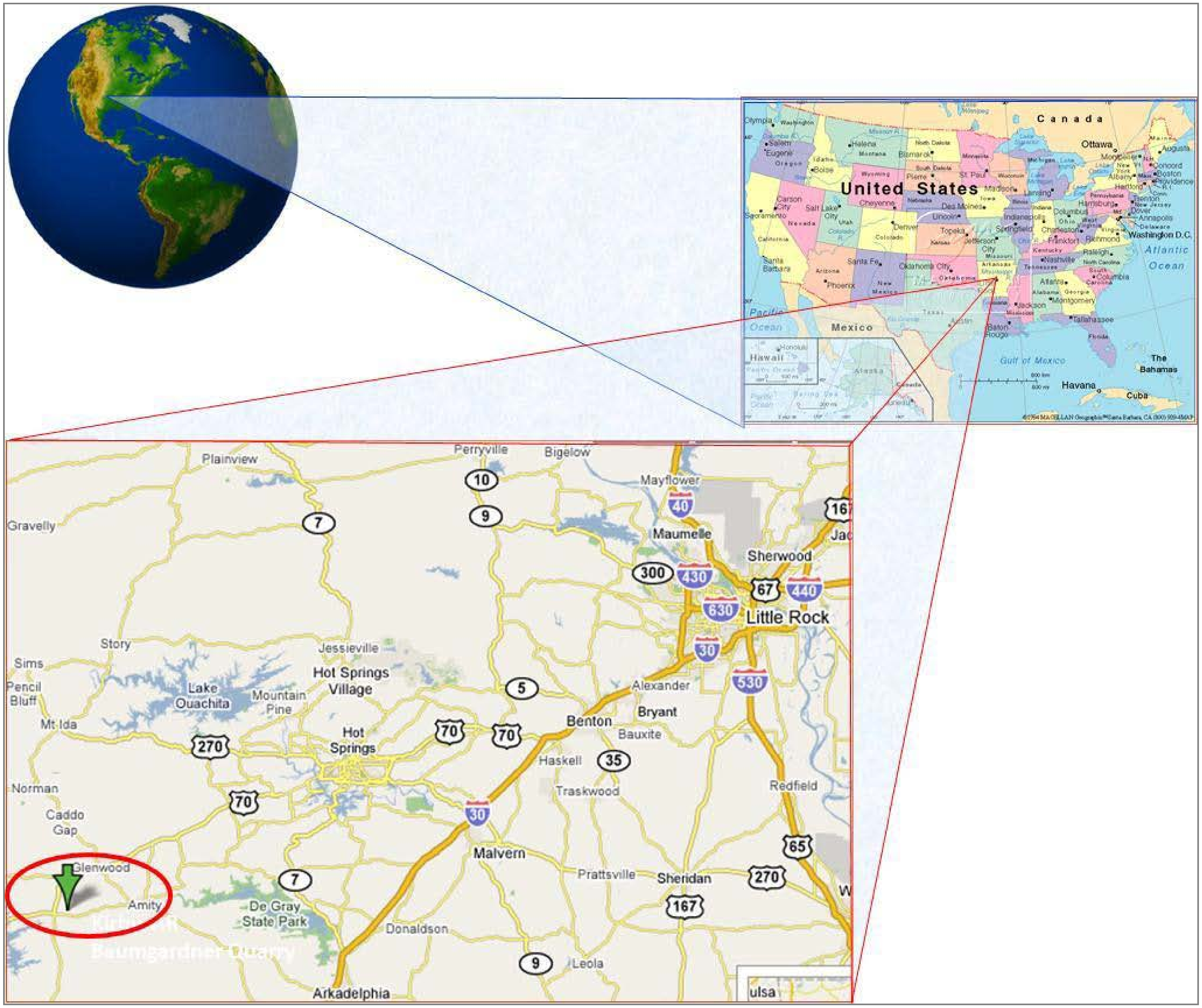

Figure 5. Image that shows the location of the study area. (Modified from Slatt 2010).

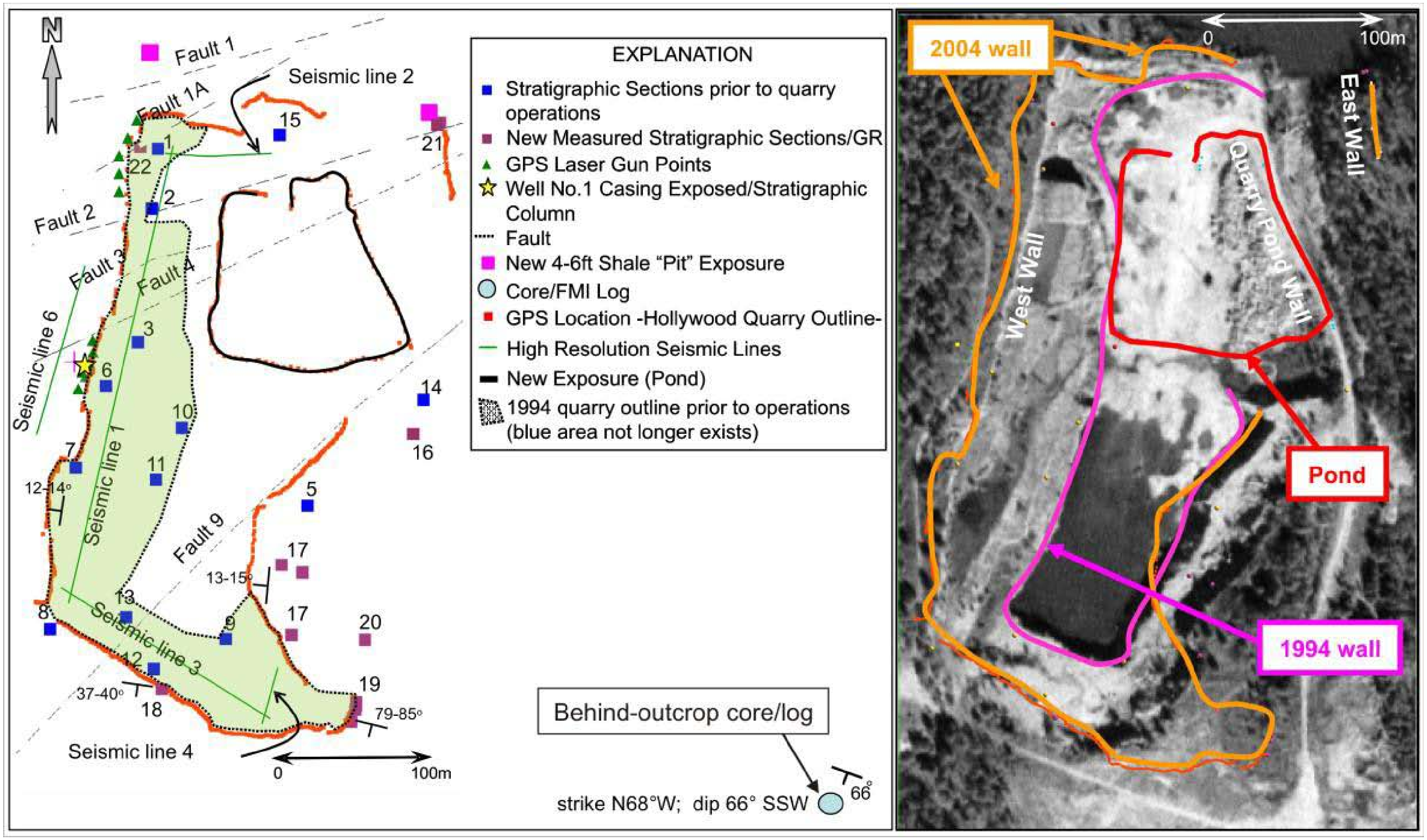

Figure 6. Goyeneche's map showing 2004 Hollywood Quarry outline (red). The aerial photograph on the right was taken prior 1994 and shows the outline of the Quarry. (Goyeneche et al 2007).

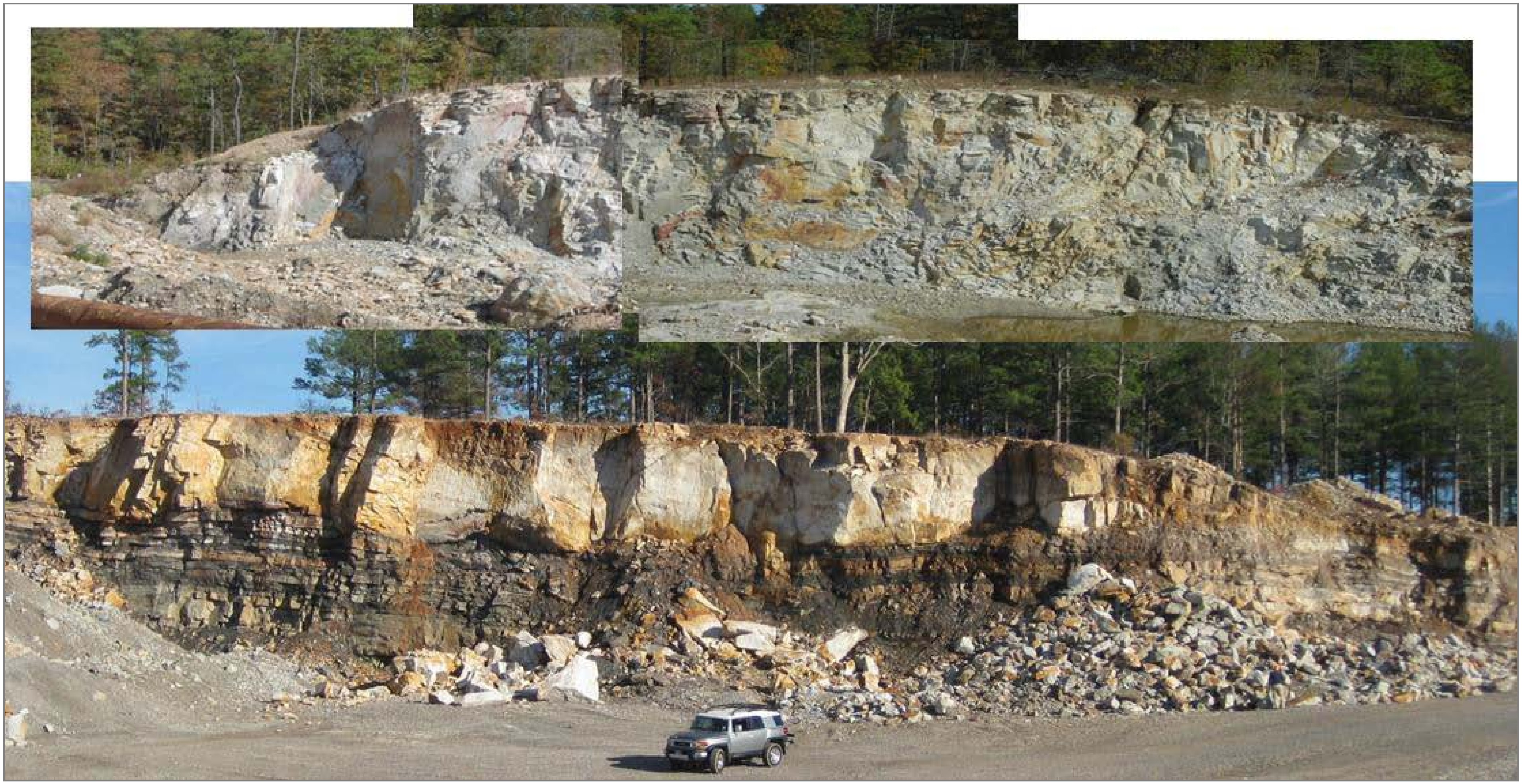

Figure 7. The Image shows on the top a photomosaic of the NE wall before the blasting, on the lower part is the same wall after the blasting.

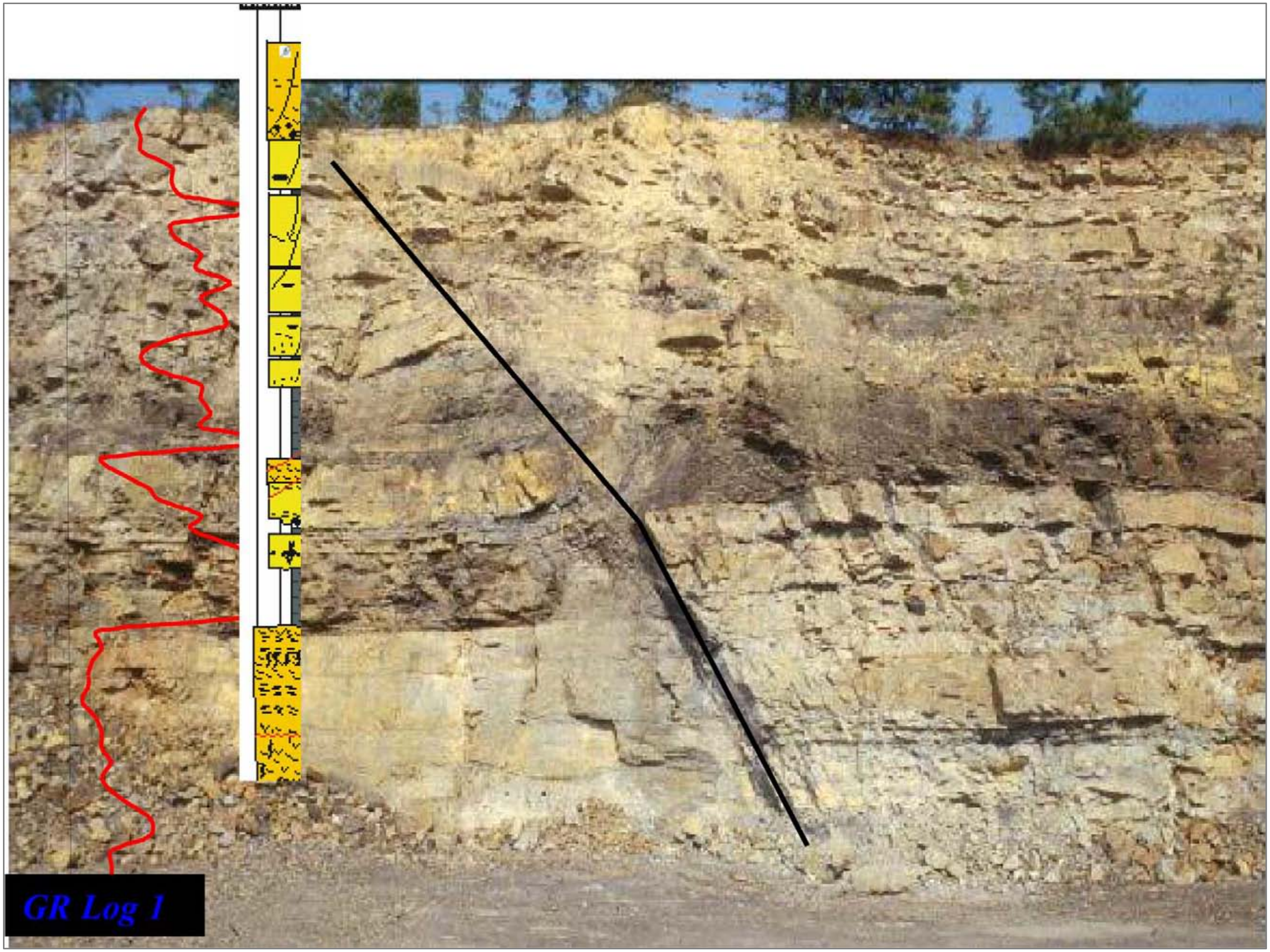

Figure 8. Image showing the stratigraphy of the West wall and some of the structural features. Modified from Slatt 2000.

Figure 9. Image showing the lithology and the dipping of the beds on the South wall.

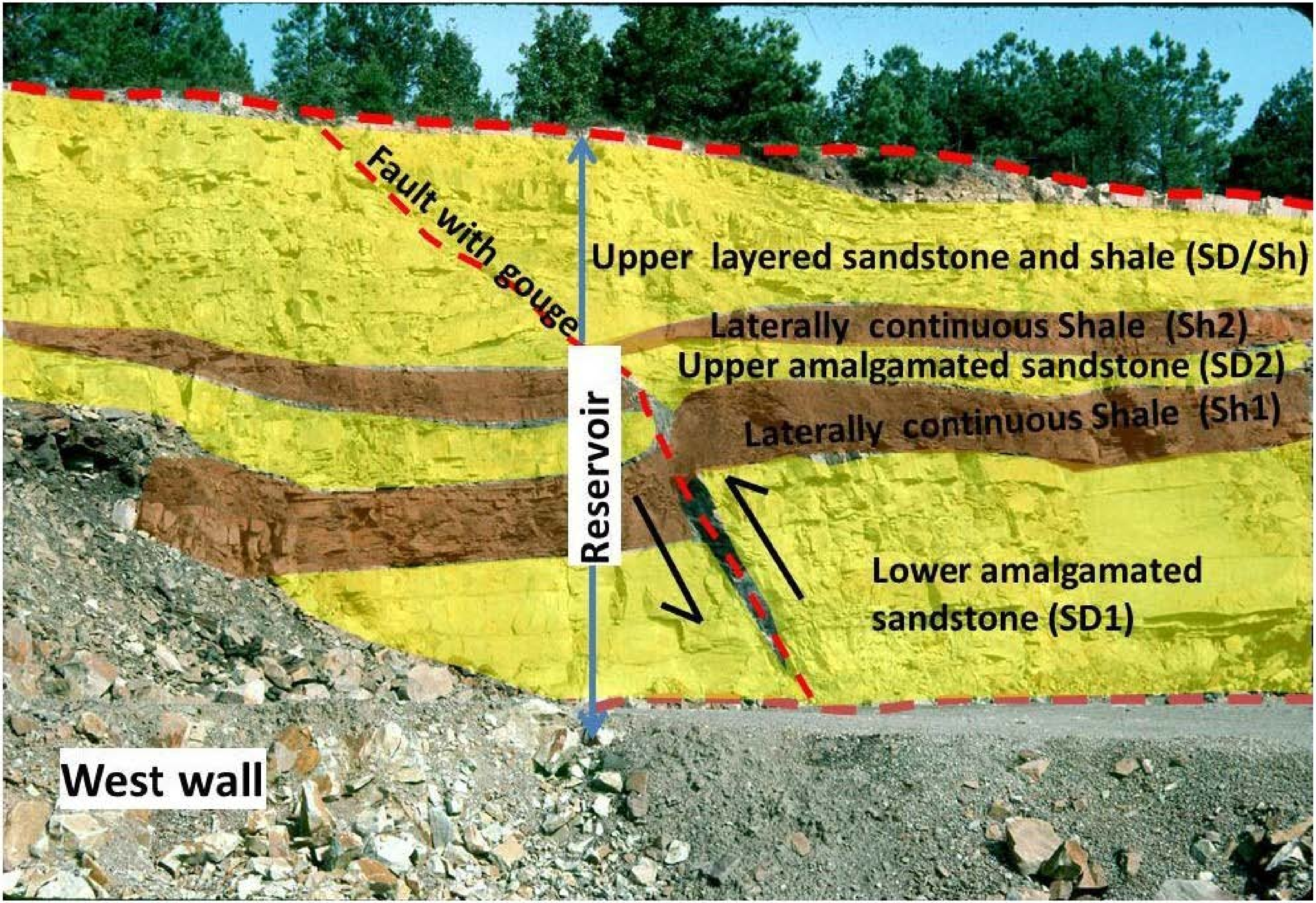

Figure 10. Image showing the natural laboratory and the different facies of the Quarry

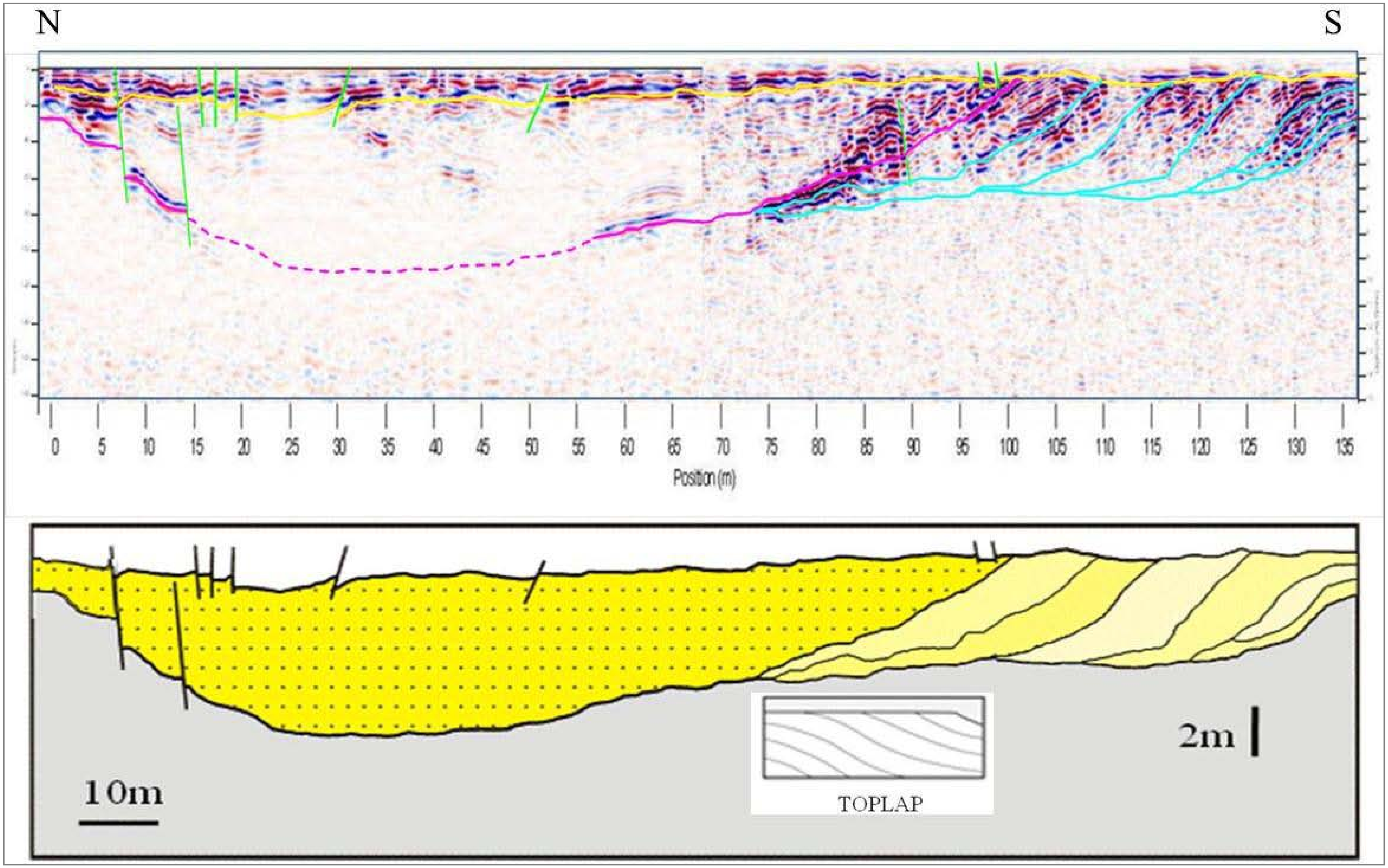

Figure 11. The image shows GPR Profile Interpretation on the top and below a sketch of the channel body formation. Brito (2010).

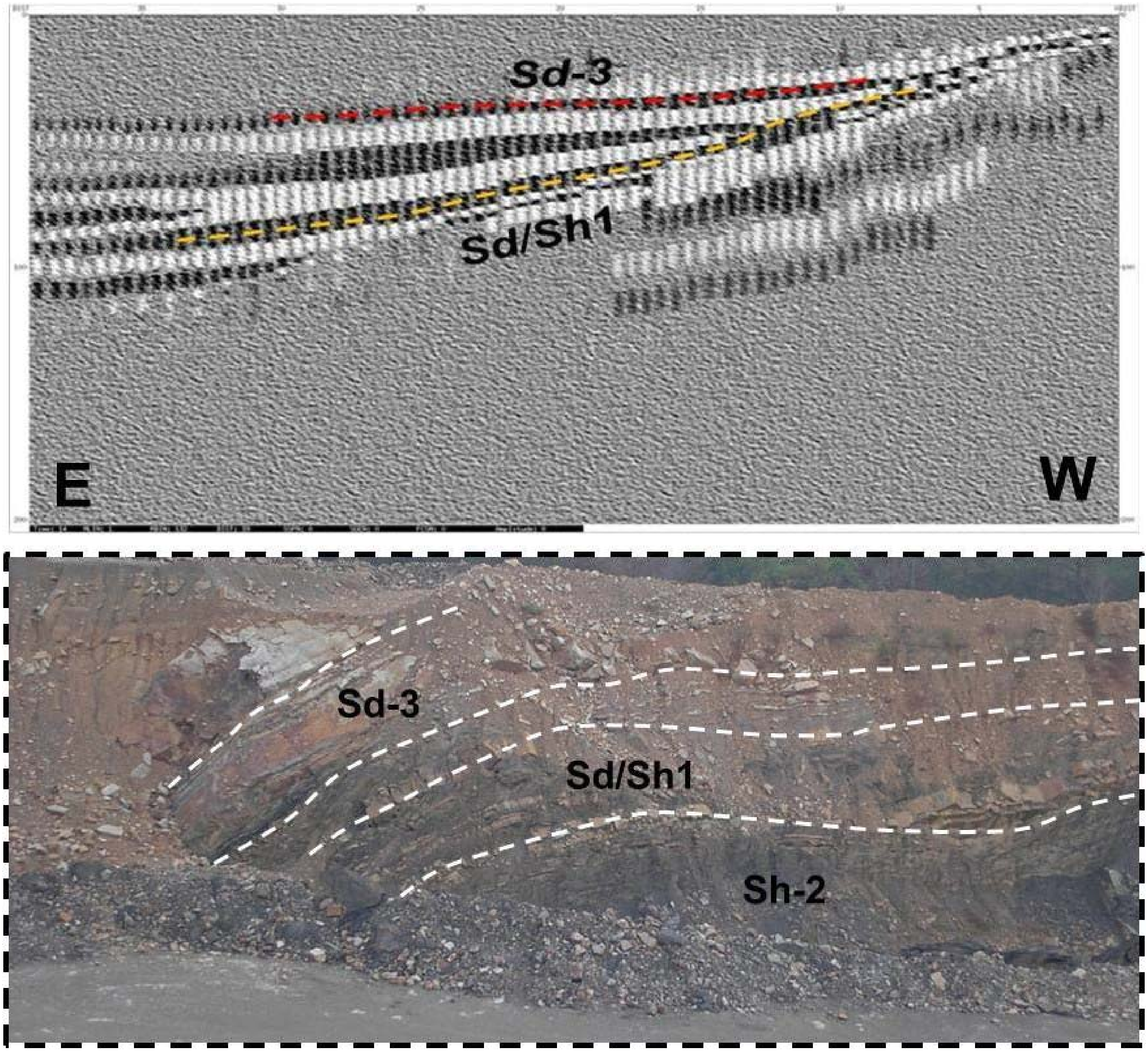

Figure 12. On the top: interpretation of the Seismic Line; below: the correlation with the outcrop geology.

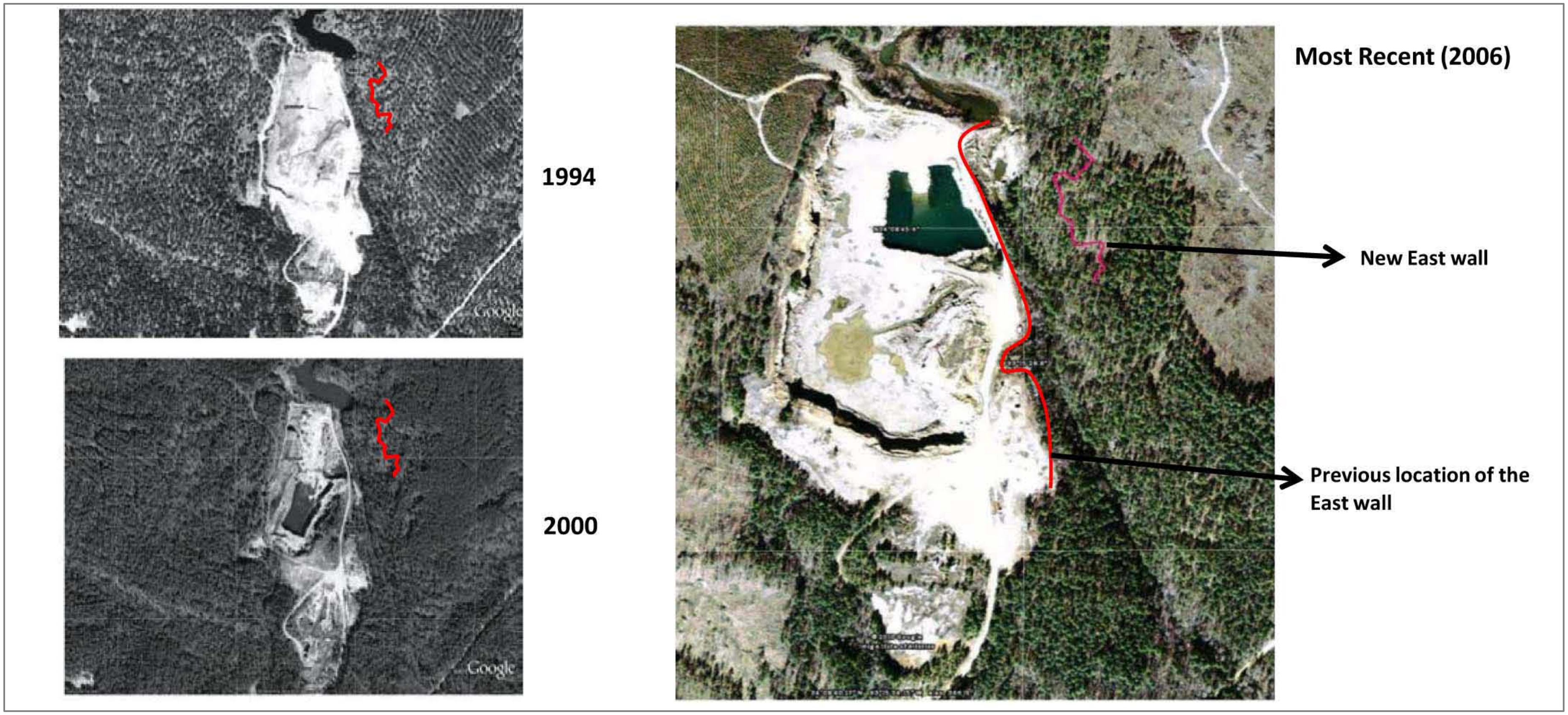

Figure 13. The images show the evolution of the different walls of the quarry through time. To the right, an illustration of the previous and the new location of the East Wall. The location of the new East Wall was determined using GPS data at 20 feet sampling intervals.

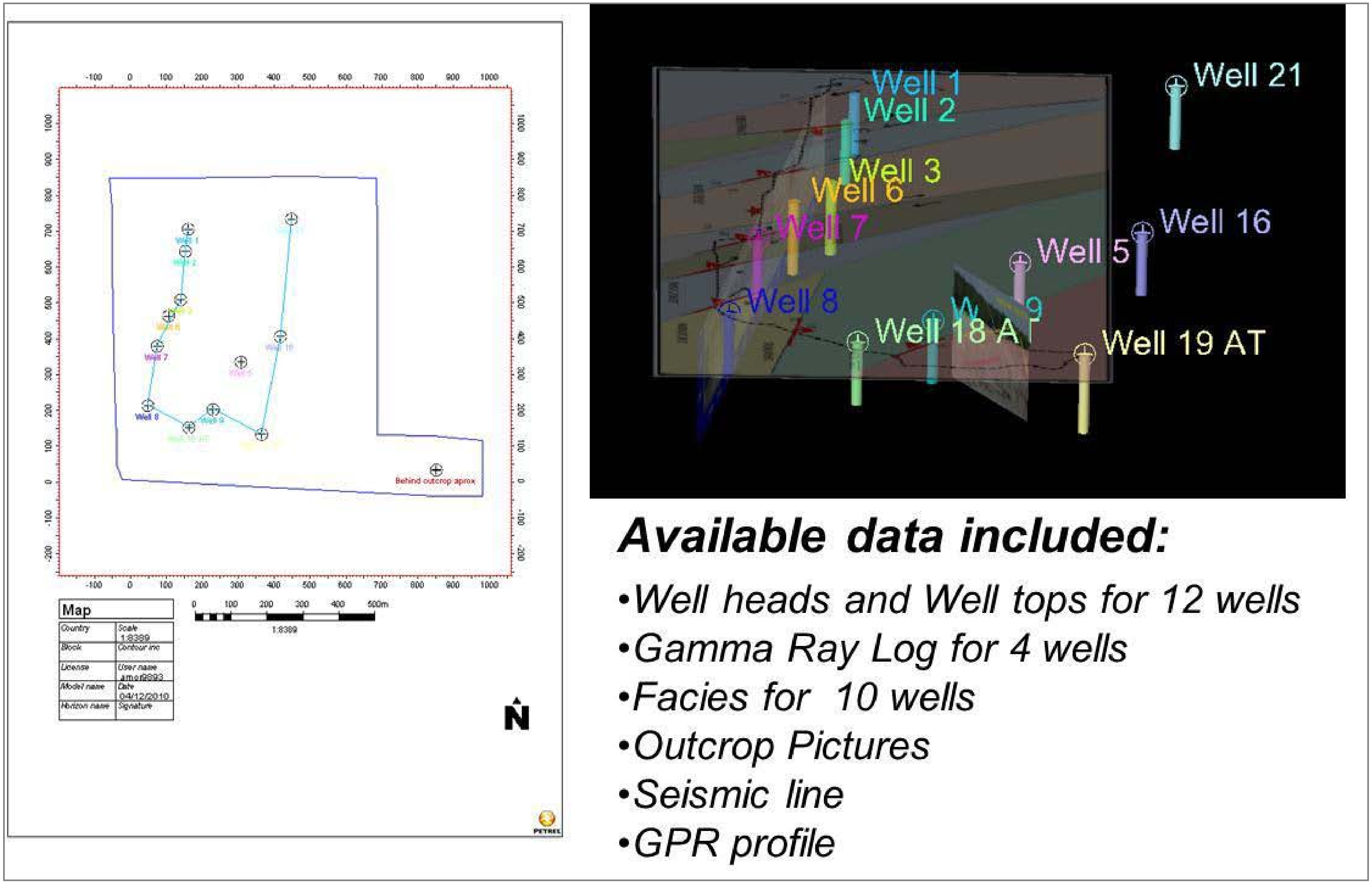

Figure 14. The image shows all the data available to build the model.

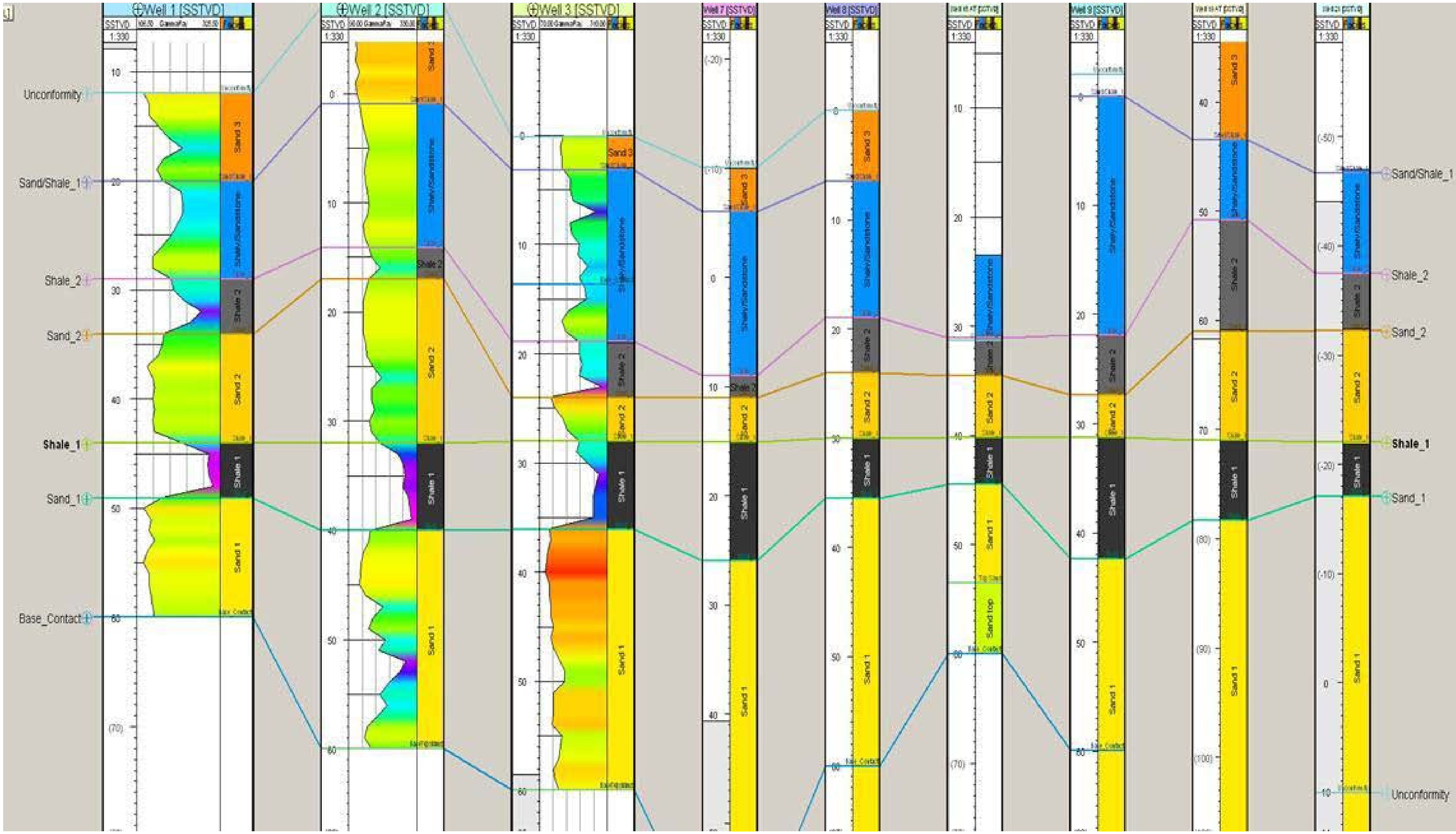

Figure 15. Well top correlation of the different facies present on the Quarry.

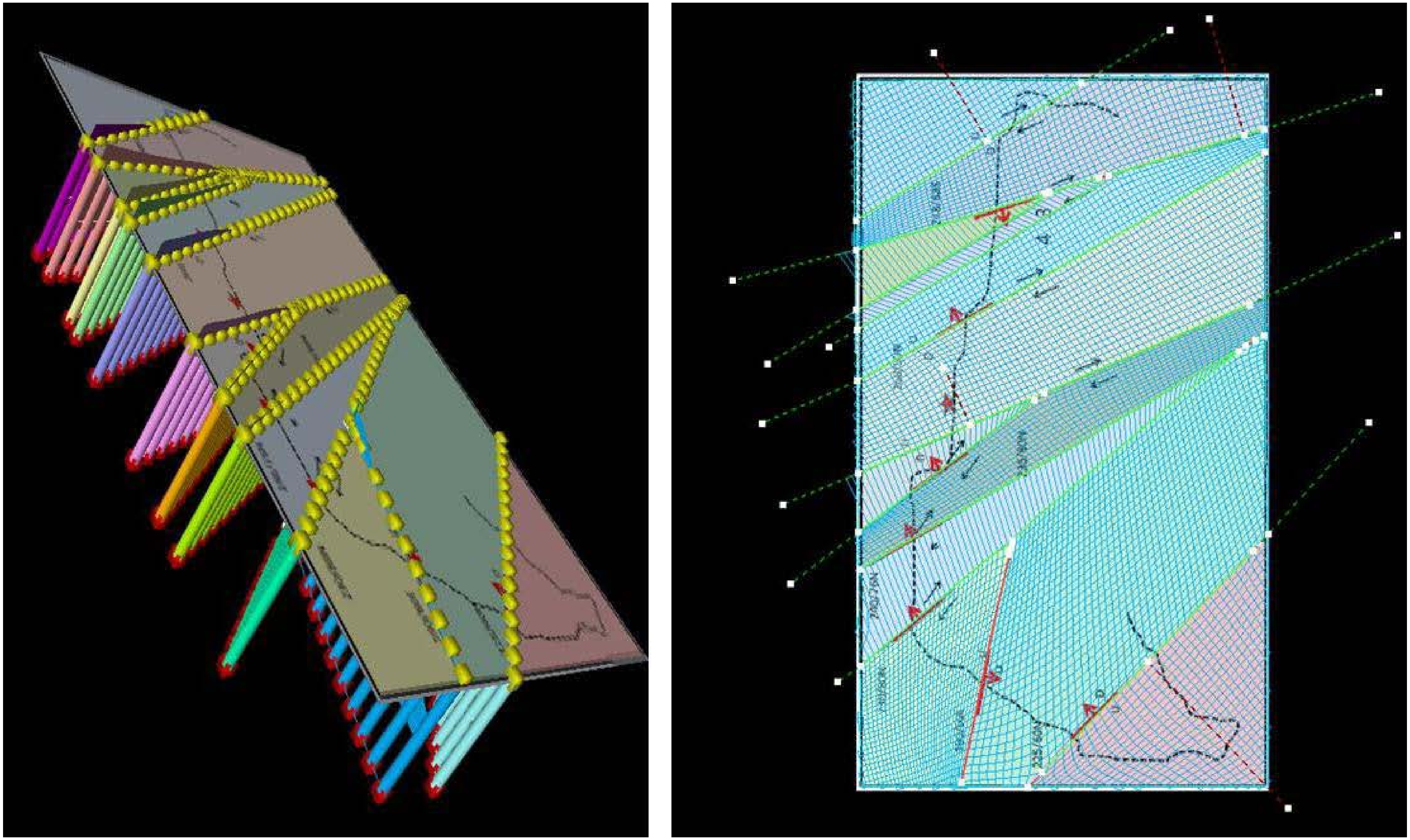

Figure 16. The image shows on the right Fault modeling and on the left the pillar gridding.

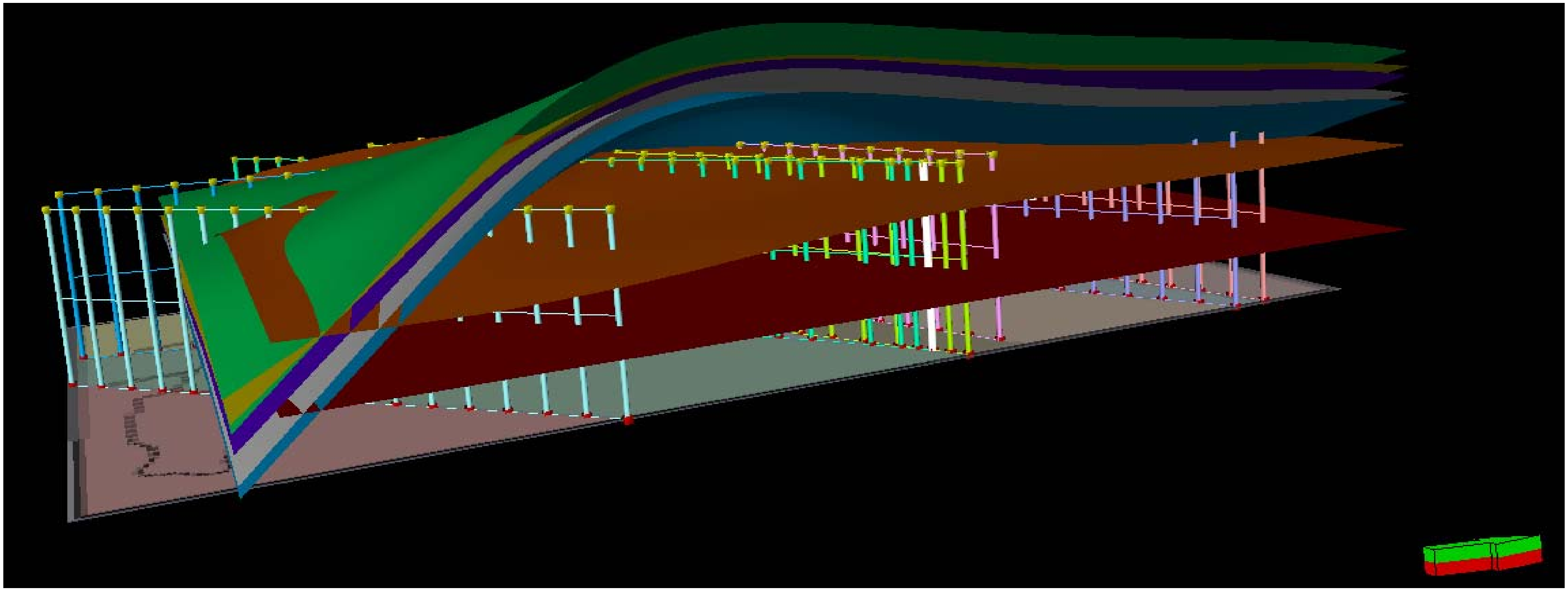

Figure 17. The image shows a screen shot of the different horizons of the model.

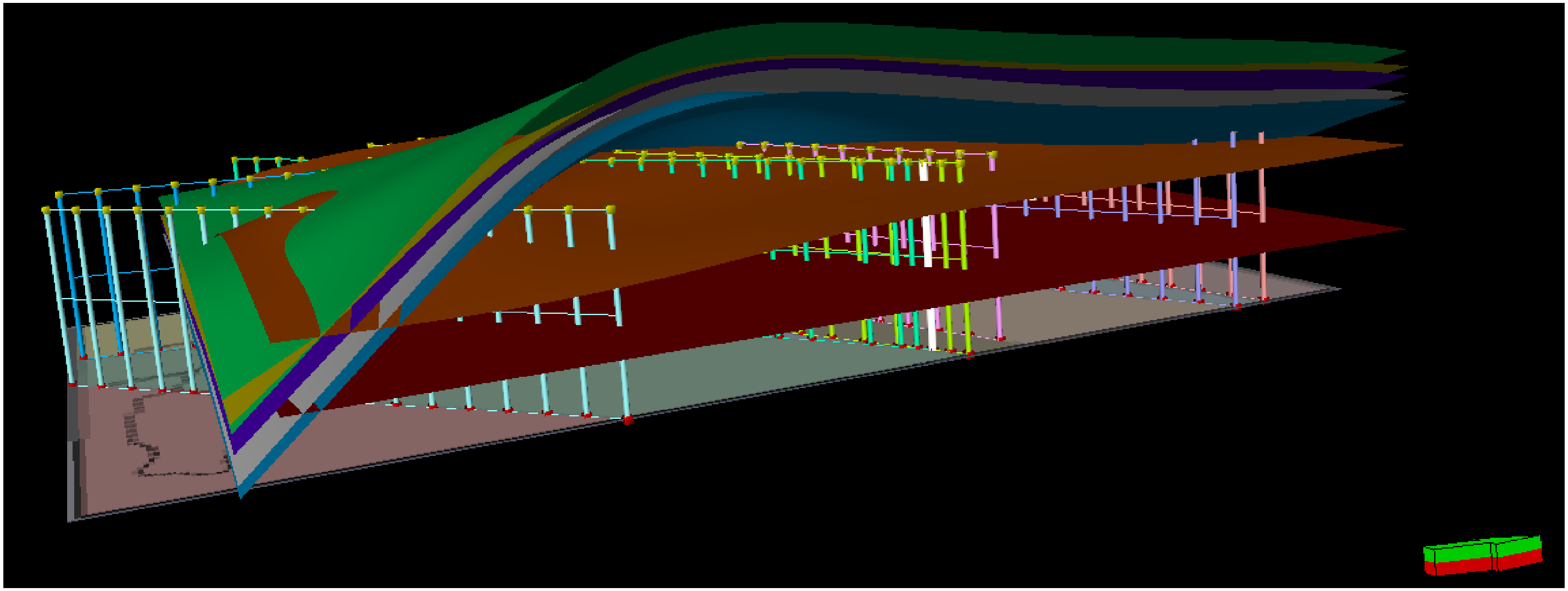

Figure 18. The image shows the edge of the facies model.

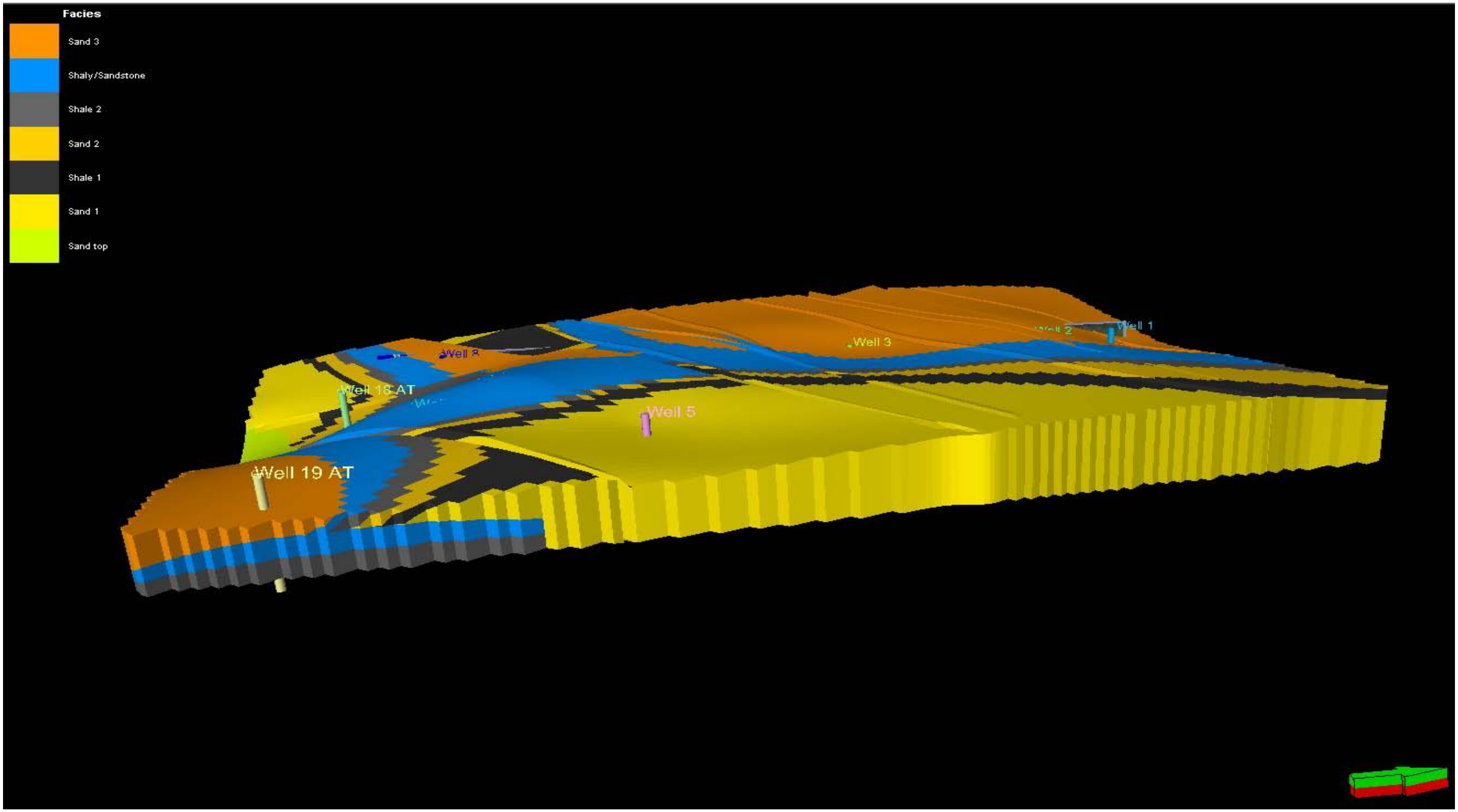

Figure 19. The image shows a 3D cube of the facies model.

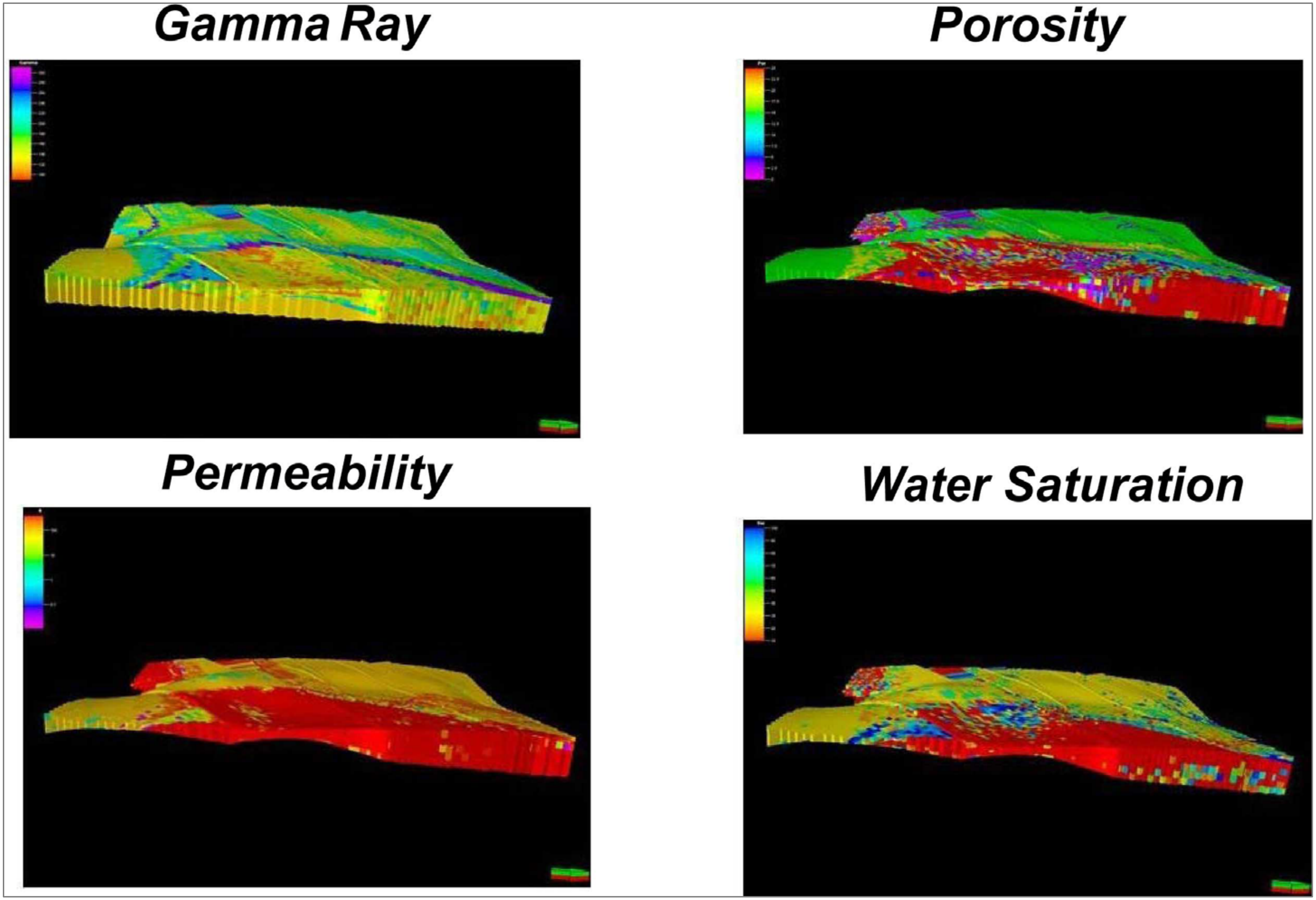

Figure 20. Images showing petrophysical modeling, four attributes were modeled.

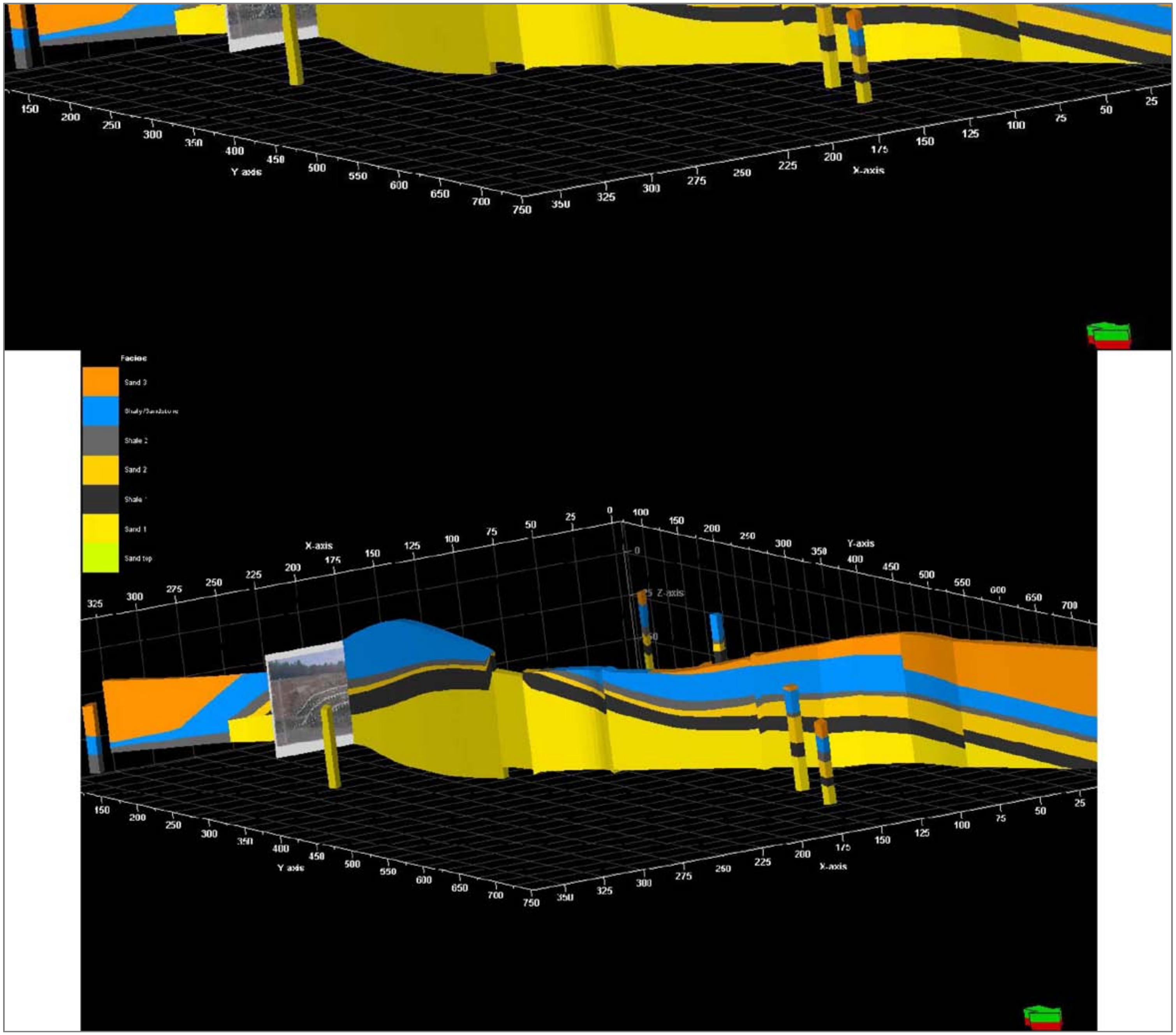

Figure 21. Seismic line correlated with the facies model.

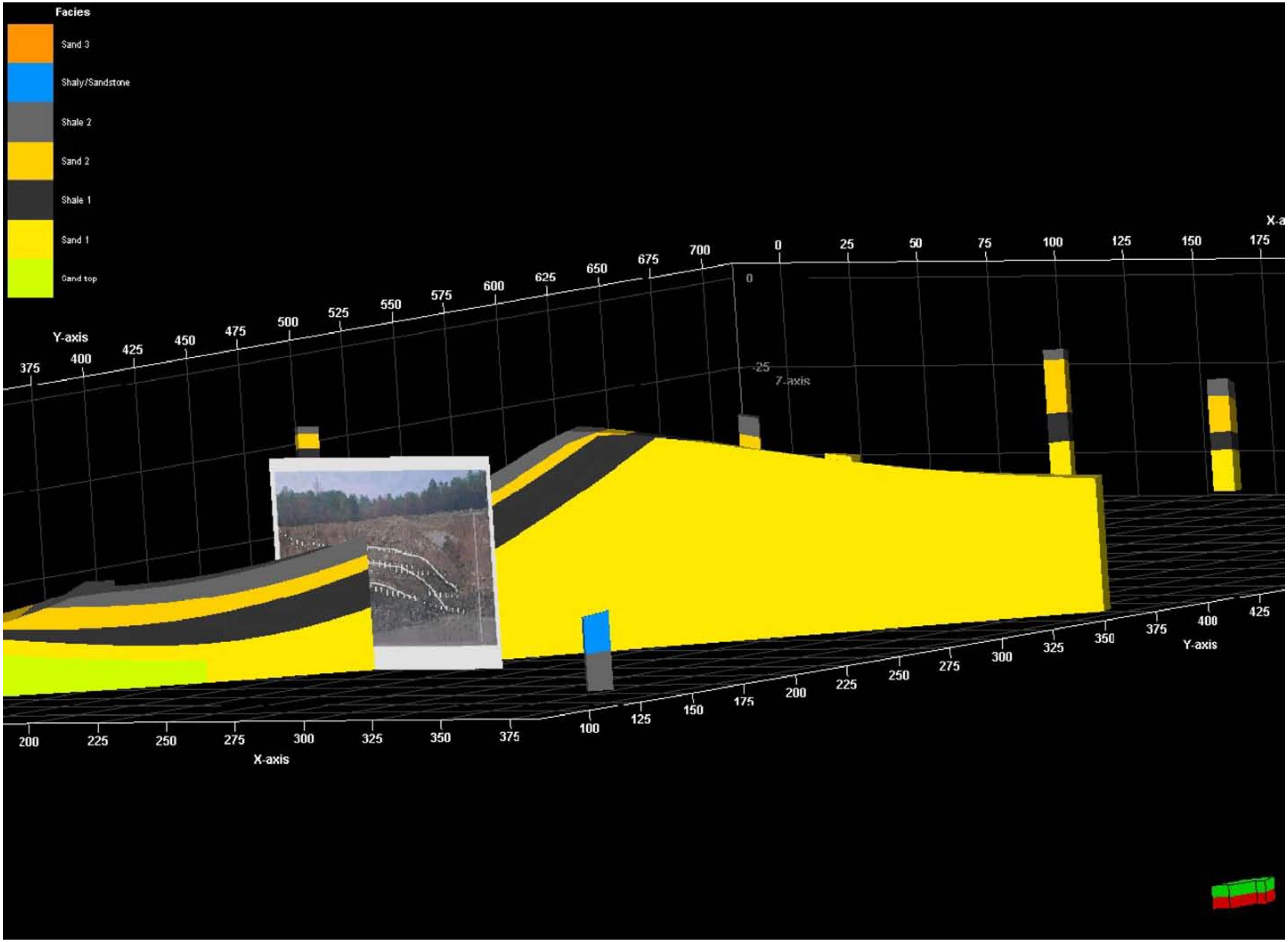

Figure 22. Rear view of the Seismic line correlated with the facies model.

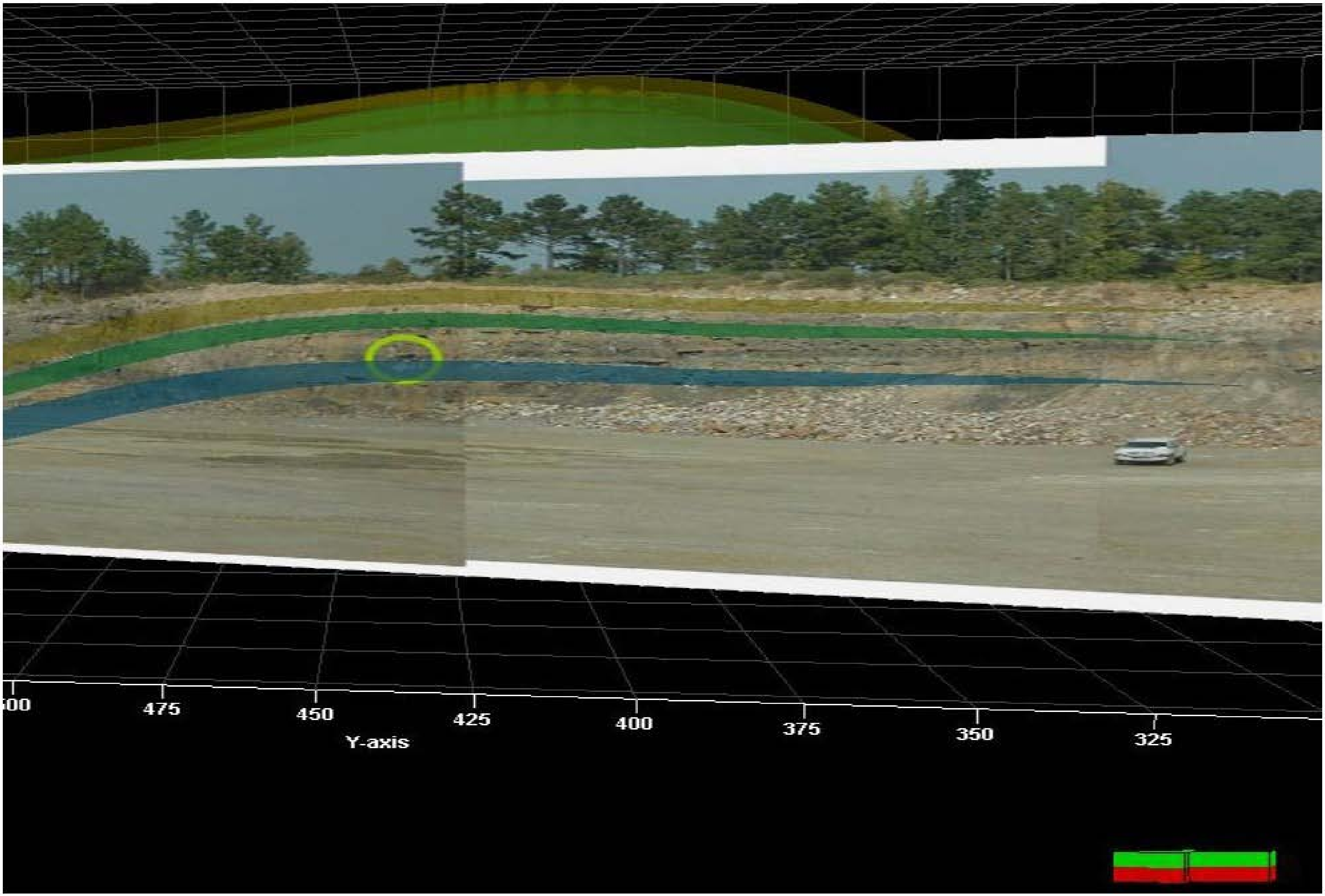

Figure 23 Image of the West wall correlated with the surfaces of three different facies.

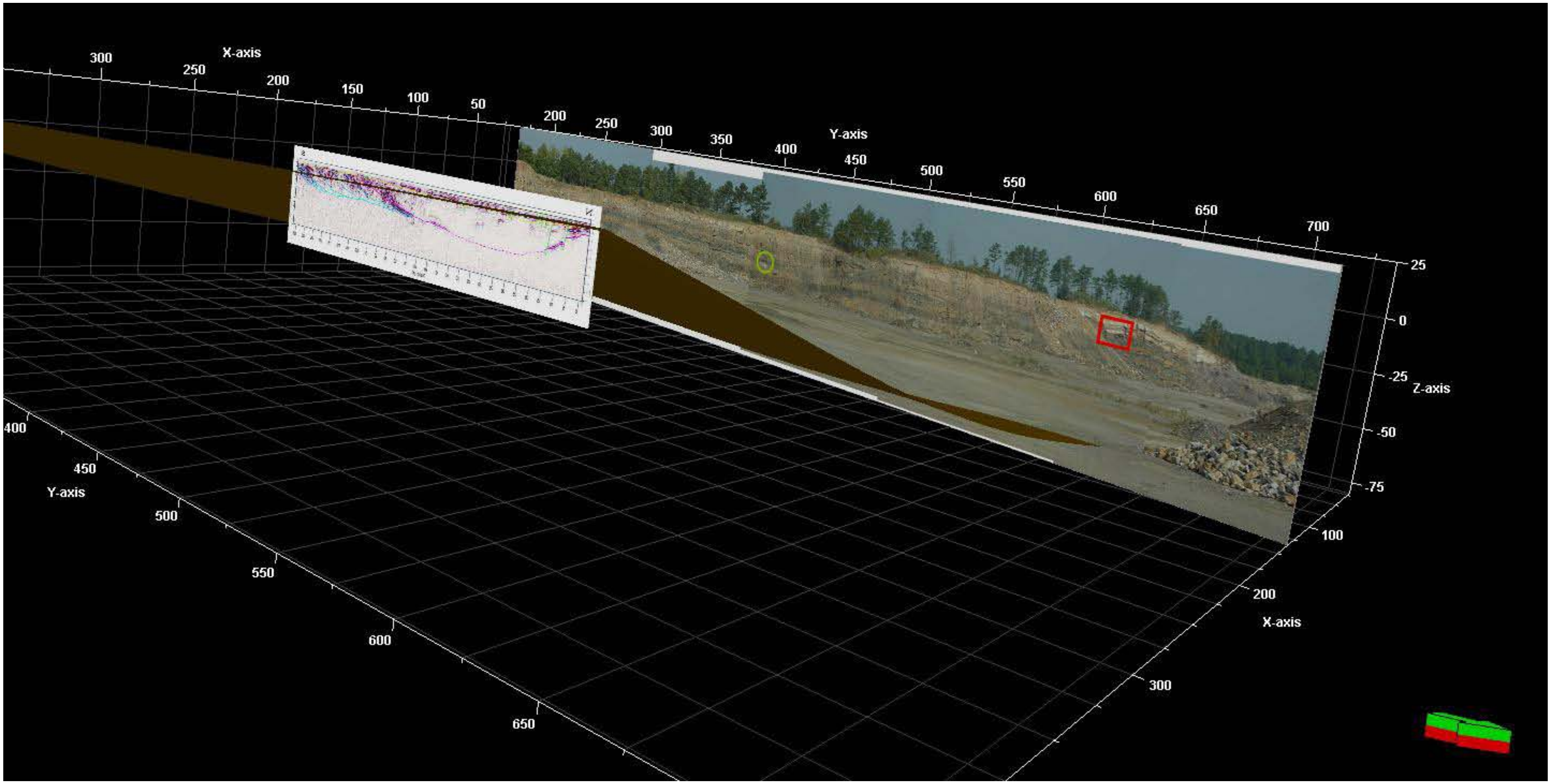

Figure 24. The image shows the top sand surface, it is evident that the channel fill cannot be observed on the west wall.