PSLithofacies Prediction and 3-D Geological Model in Tight Gas Sandstone Reservoirs by Integration of Well Logs and Geostatistics Modeling*

Binfeng Cao[1], Xiaorong Luo[1], Likuan Zhang[1], Yuhong Lei[1], Bo Qin[2], and Zhenyu Zhang[1]

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Abstract

Understanding reservoir heterogeneity is important for the economic success of tight gas sandstone reservoirs. The intrinsic complexity of a reservoir is the result of depositional environment and diagenesis. In the Lower Permian Shanxi Formation of the Ordos Basin, primary sandstone texture and composition (grain size, ductile lithic sand grains) directly related to depositional variability in the delta-front environments, controls compaction and the abundance of cements and porosity.

This study highlights the upscaling of small-scale (pore- and core-scale) lithofacies heterogeneity for accurate field-scale geological modeling using well logs. Five lithofacies are defined based on detrital texture and composition, diagenetic features, and pore space properties. Detrital quartz-rich sandstones (quartzarenitic and rare sublitharenitic) show the highest reservoir quality; these sandstones can be identified by low gamma ray, low bulk density, and high deep resistivity log values. Sandstones of the poorest reservoir quality are rich in ductile lithic grains and clay matrix or tightly cemented with carbonate. Ductile lithic-rich sandstones (litharenitic and most sublitharenitic) are identified by high gamma ray, high bulk density, and low deep resistivity values. Tight carbonate-cemented intervals are identified by high bulk density values. Tuffaceous quartz sandstones with poor reservoir quality show some overlaps in well logs from other lithofacies. A model based on principal component analysis (PCA) shows better identification of the five lithofacies than biplots of well logs.

A 3D architectural model of channel-belts is constructed based on multiple evolutionary maps of regional sedimentary microfacies. Lithofacies are modeled further by interpreted well data using the sequential Gaussian method. At field scale, detrital quartz-rich sandstones are distributed mainly in the lowermost and uppermost intervals of the Shanxi Formation. Tuffaceous quartz sandstones are found only in the lowermost intervals. At a channel scale, the dominant lithofacies are detrital quartz-rich sandstones in the middle–lower interval of the distributary channels, changing gradually upward into ductile lithic-rich sandstones. The 3D lithofacies model is validated by correlation with gas production test which suggests it is a helpful predictive model for sweet spots in tight sandstone reservoirs.

References Cited

Cao, B.F., 2017, Availability of Tight Gas Sand Reservoir and Formation: A Case Study from Upper Paleozoic Shanxi Formation, Southeastern Ordos Basin: Ph.D. Dissertation, University of Chinese Academy of Sciences, p. 174.

Ozkan, A., S.P. Cumella, K.L. Milliken, and S.E. Laubach, 2011, Prediction of Lithofacies and Reservoir Quality Using Well Logs, Late Cretaceous Williams Fork Formation, Mamm Creek Field, Piceance Basin, Colorado: American Association of Petroleum Geologist Bulletin, v. 95/10, p. 1699-1723.

ABSTRACT

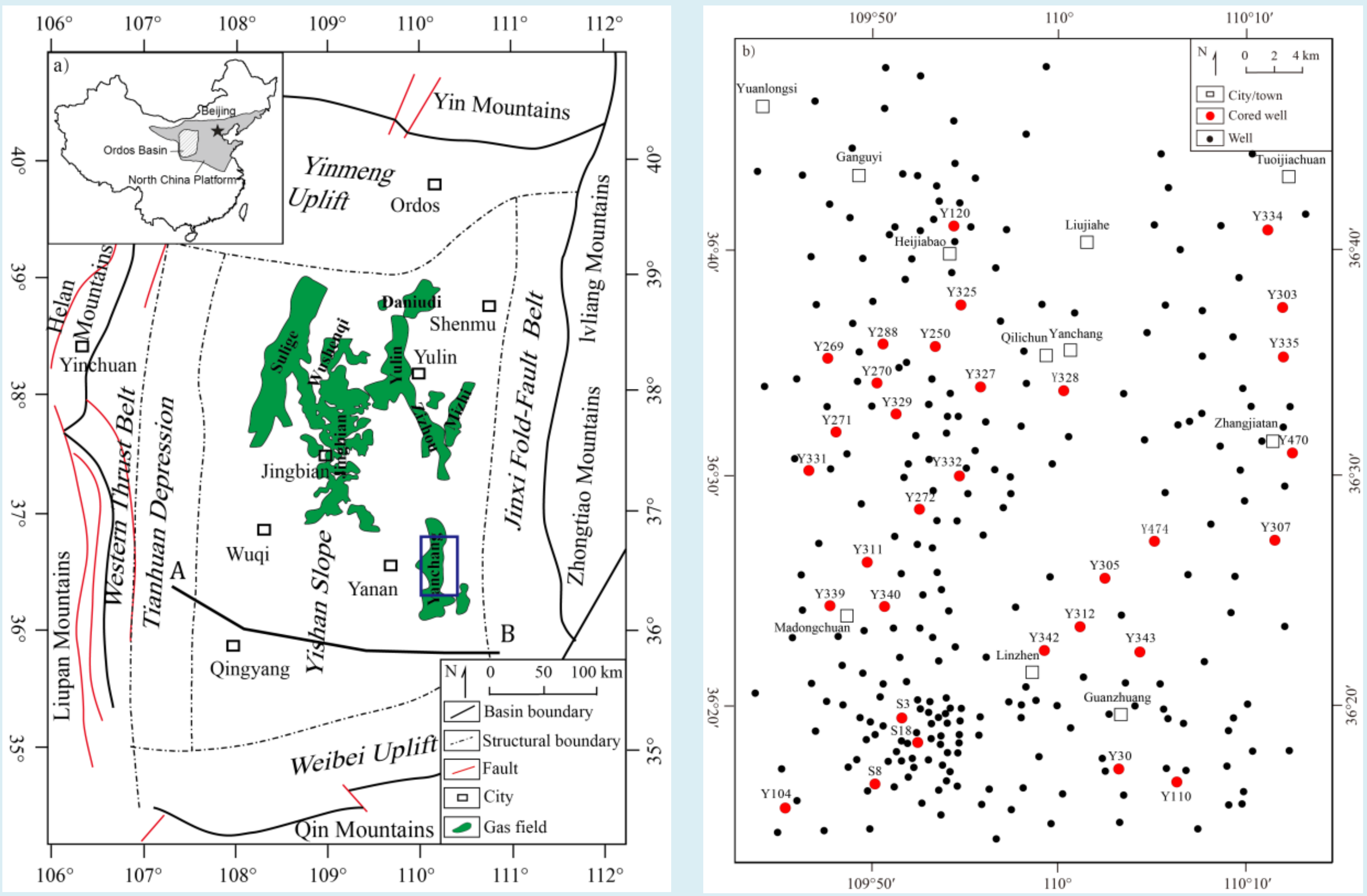
Understanding reservoir heterogeneity is important for the economic success of tight gas sandstone reservoirs (Ozkan et al., 2011; Cao, 2017). The intrinsic complexity of a reservoir is the result of depositional environment and digenesis. In the Lower Permian Shanxi Formation of the Ordos Basin, primary texture and mineral composition of sandstones (grain size, ductile lithic sand grains) directly related to provenance and depositional variability in the delta-front environments, controls compaction and the abundance of cements and porosity.

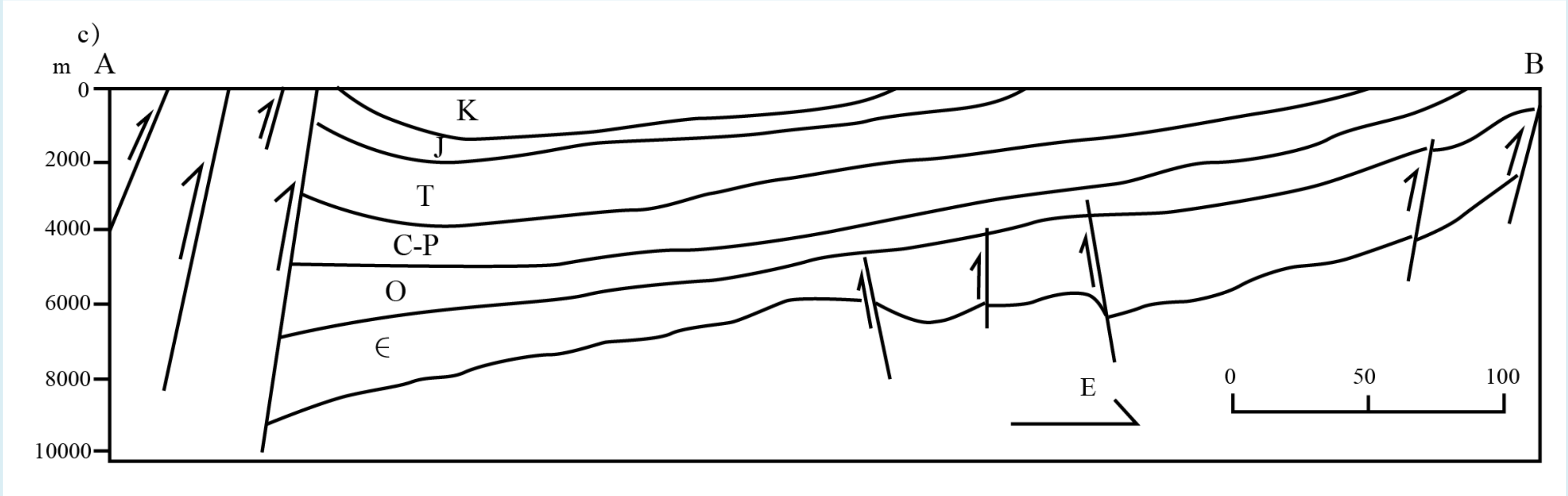
This study highlights the upscaling of small-scale (pore- and core-scale) lithofacies heterogeneity for accurate field-scale geological modeling using well logs. Five sandstone lithofacies are defined based on detrital texture and composition, diagenetic features, and pore type. Detrital quartz-rich sandstones (quartzarenitic to sublitharenitic) show a patchy cementation in minor amounts dominated by a combination of quartz overgrowth, ankerite or calcite, and clays. These sandstones exhibit the highest reservoir quality and can be identified by low gamma ray, compensated neutron, and bulk density; and high acoustic and deep resistivity log values. Sandstones with the poorest reservoir quality are rich in ductile lithic grains and detrital matrix or are tightly cemented with carbonate. Highly compacted ductile lithic-rich sandstones (sublitharenitic to litharenitic) are identified by high gamma ray, compensated neutron, and bulk density; and low acoustic and deep resistivity values. Tightly carbonate-cemented intervals are identified by high bulk density and low acoustic values. Tuffaceous quartz sandstones show some overlaps in well logs from other lithofacies. A model based on principal component analysis (PCA) show better identification of the five lithofacies than biplots of well logs.

In this study, a 3D architectural model of channel-belts is constructed based on multiple evolutionary maps of regional depositional microfacies. Lithofacies are modeled further by interpreted well data using the sequential Gaussian method. At field scale, detrital quartz-rich sandstones are distributed mainly in the lowermost and uppermost intervals of the Shanxi Formation. Tuffaceous quartz sandstones are found only in the lowermost intervals. At a channel scale, the dominant lithofacies are detrital quartz-rich sandstones in the middle-lower interval of distributary channels and the axis, changing gradually upward and at the marginal parts into tuffaceous quartz sandstones or ductile lithic-rich sandstones. Tightly carbonate-cemented sandstones are randomly enclosed in ductile lithic-rich sandstones. The 3D lithofacies model is validated by correlation with gas production test which suggests it is a helpful predictive model for sweet spots in tight sandstone reservoirs.

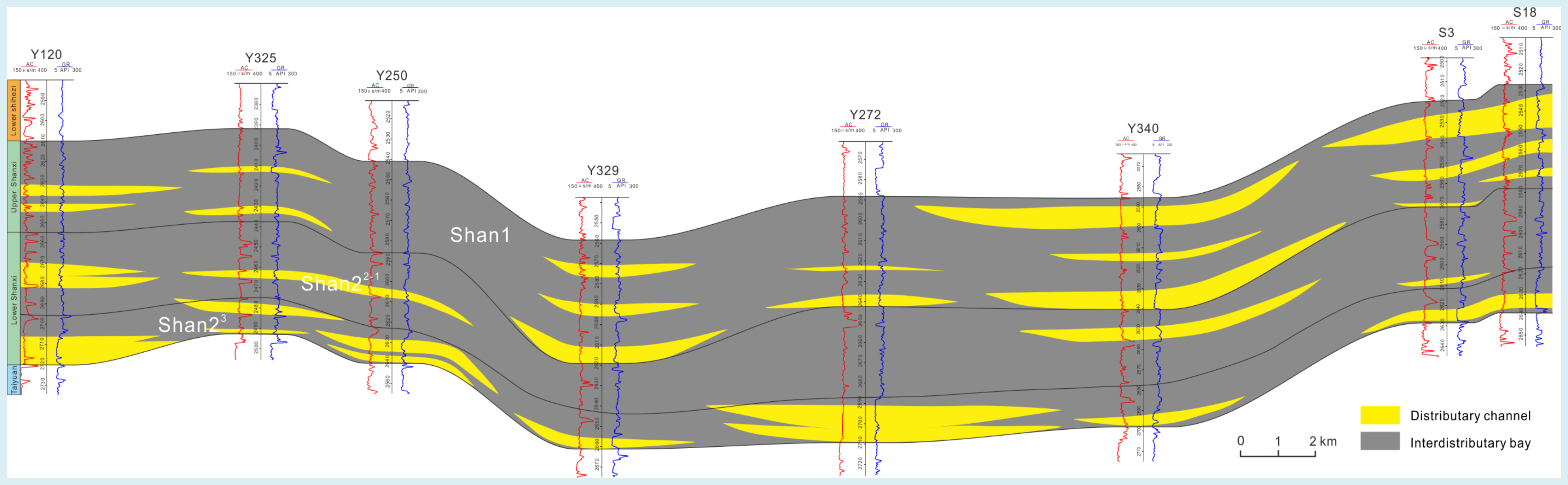
GEOLOGICAL SETTING

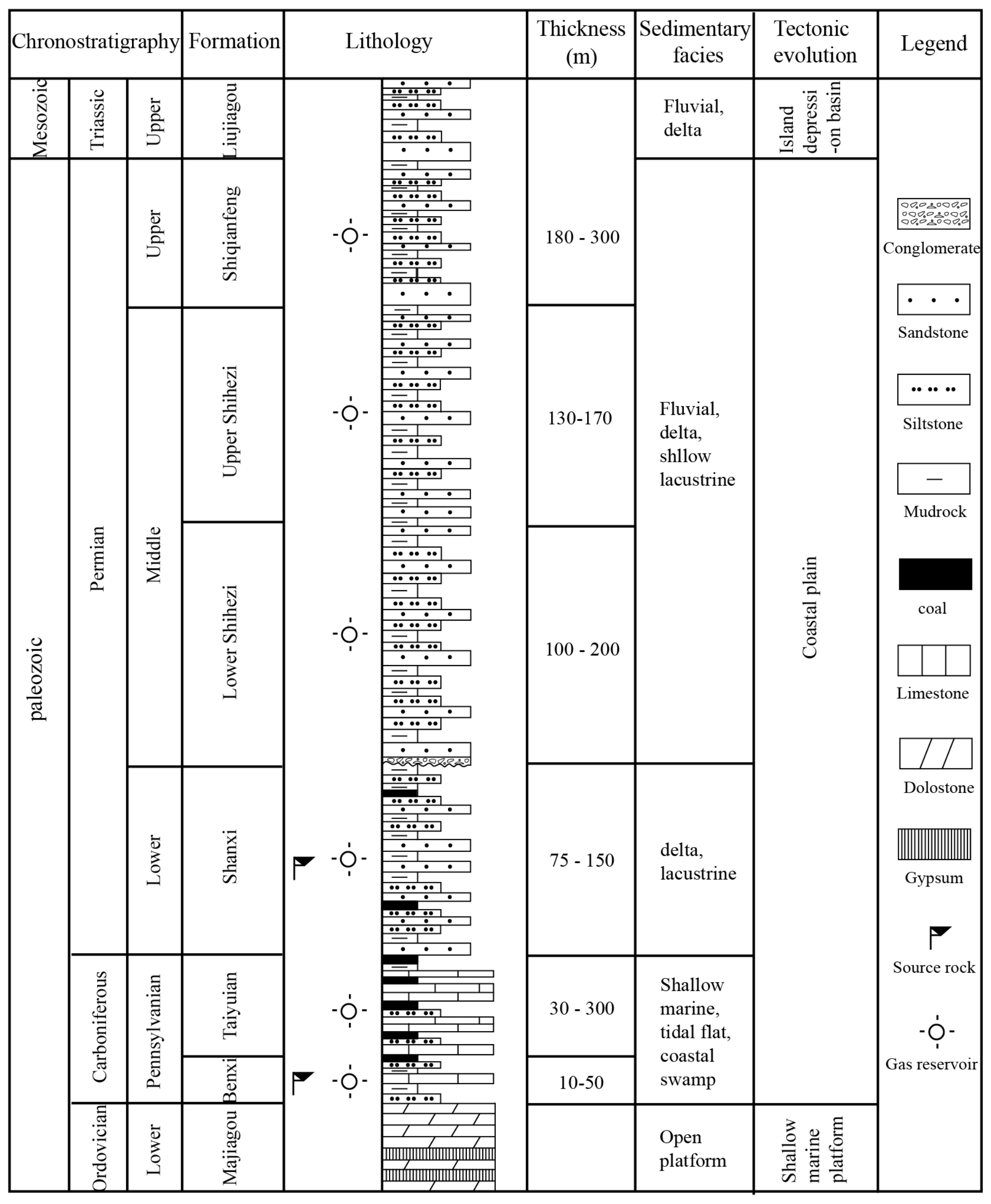
Basin structural units and wells in study area





W-E structural section illustrating a large gently west-dipping Monocline in the principal part of the southern basin.





Stratigraphic culumn of Upper Paleozoic

The Shanxi formation represents one major regressive succession in which subaqueous delta-front facies predominate. Lower part of the formation is marine influenced.

Gas in the study area is mostly produced from large stratigraphic–lithologic traps. The Shanxi Formation contains deep gray mudstones, carbargilites interbedded with coalbeds , which are highly mature to over mature and serve as good source rocks. Gas accumulations have also good sealing capability. Reservoir charaterisitcs largly determine where sweet spots of tight gas are located.

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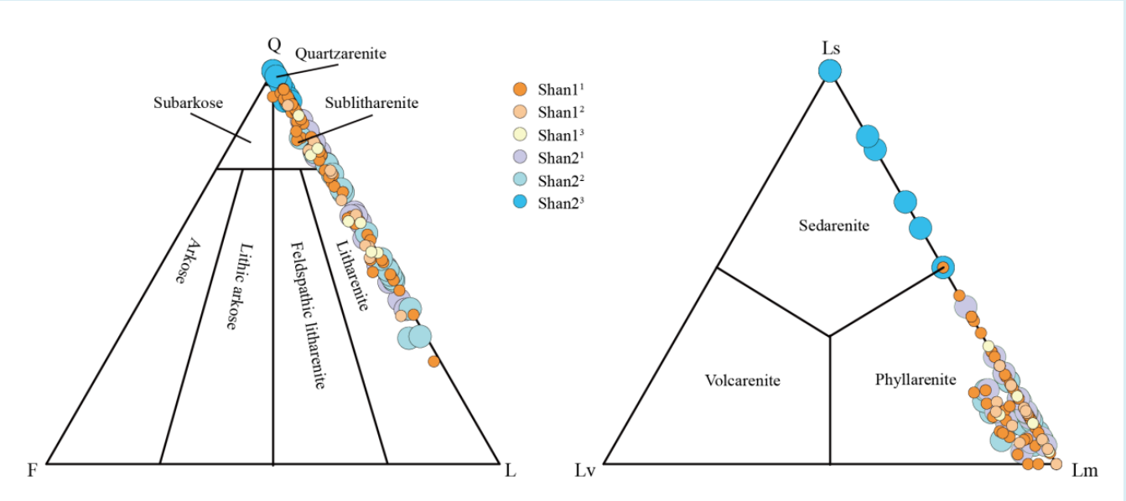
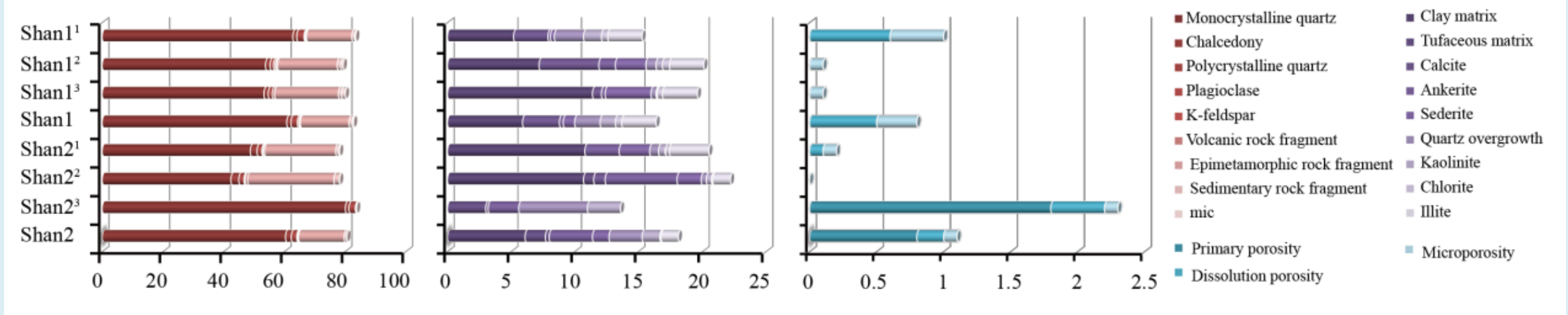
FRAMEWORK COMPOSITION AND TEXTURE

The sandstones are coarse- to fine grained. Detrital grains are mainly angular to subangular. Sorting varies from moderately to well sorted. The composition varies from quartzarenite to litharenite. Quartzarenite dominates Shan2³.

Low-grade metamorphic rock fragments dominate lithic populations, including schist, phyllite and slate.

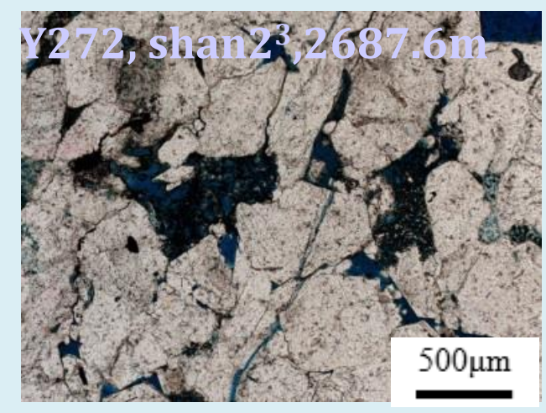


Sandstone QFL triangular classification

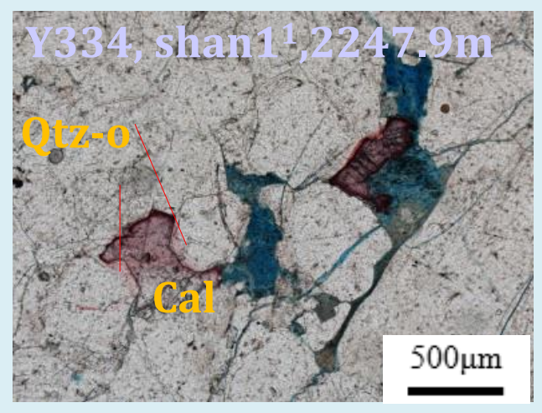


Detrital and authigenic mineral, pore contents for different stratigraphic units

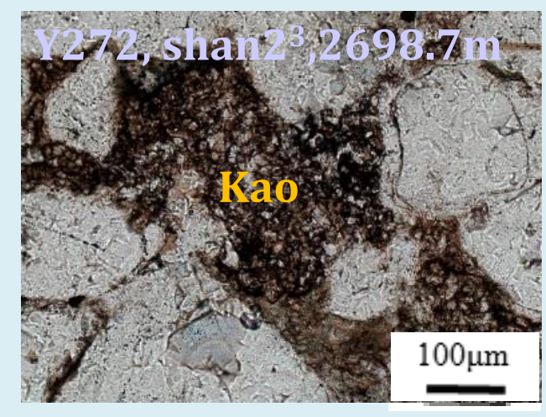
IMPORTANT DIAGENETIC FEATURES



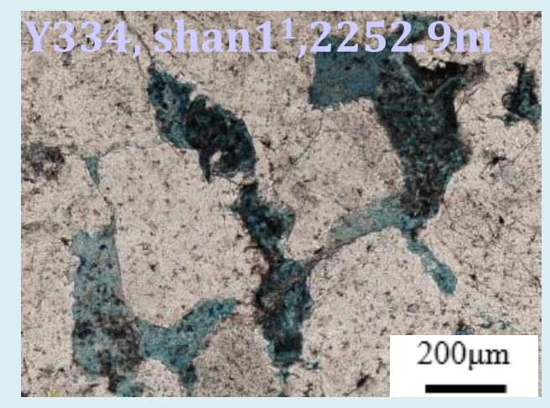
Intragrain and intergrain micro-fractures



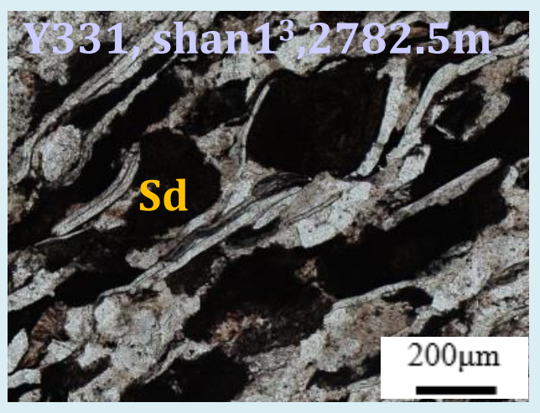
Calcite displaying a rather patchy and local cementation



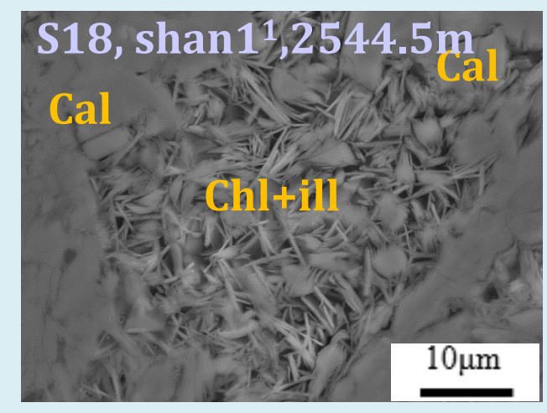
Tuffaceous matrix showing alteration into kaolinite



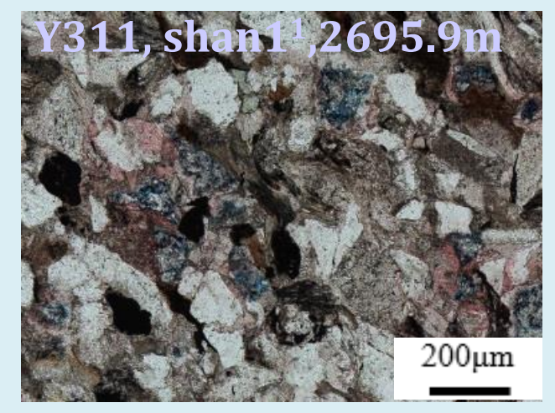
Dissolved fragments deformed between detrital quartz



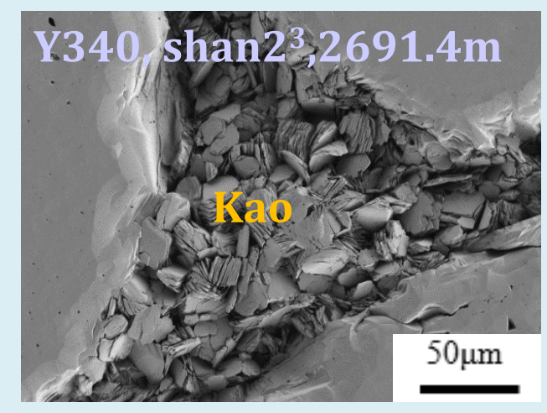
Cryptocrystalline siderite concentrated along mica-rich lamination



chlorite+illite cements engulfed by calcite

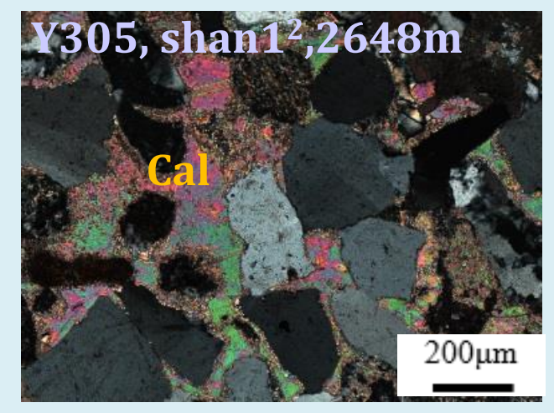


Lithic fragments altered and smeared on surfaces of quartz grains

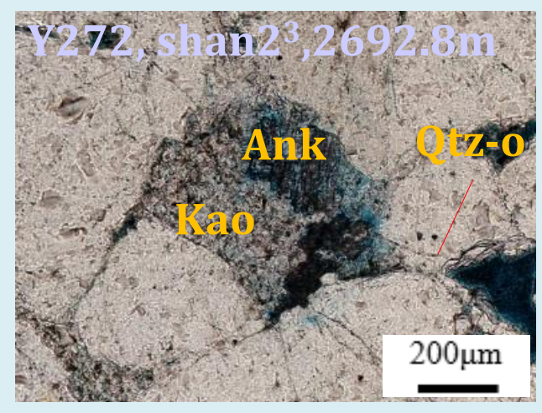


Pseudohexagonal kaolinite

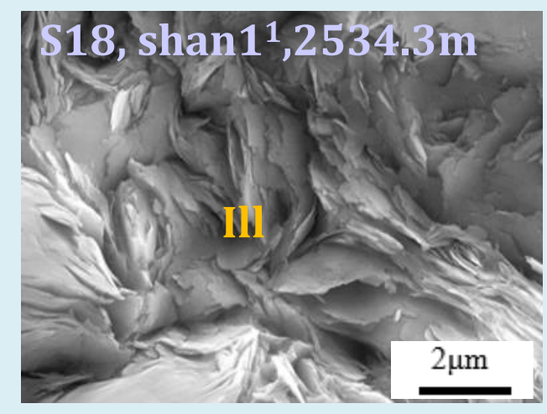
Chlorite included by illite cement



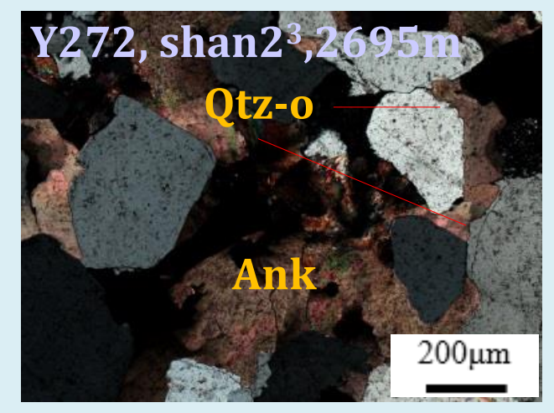
Calcite representing a poikilotopic texture and local replacement of grains



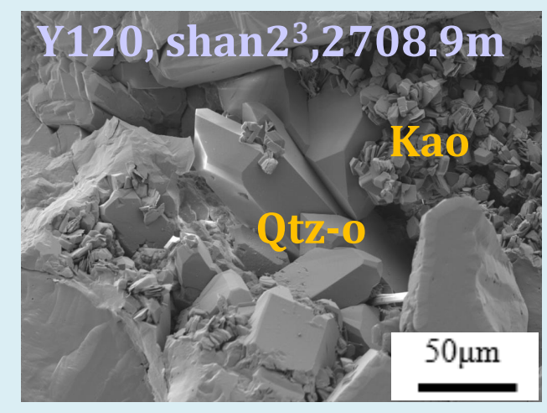
Kaolinite drived from feldspar dissolution, engulfed by quartz and ankerite cements



Flaky illite cement



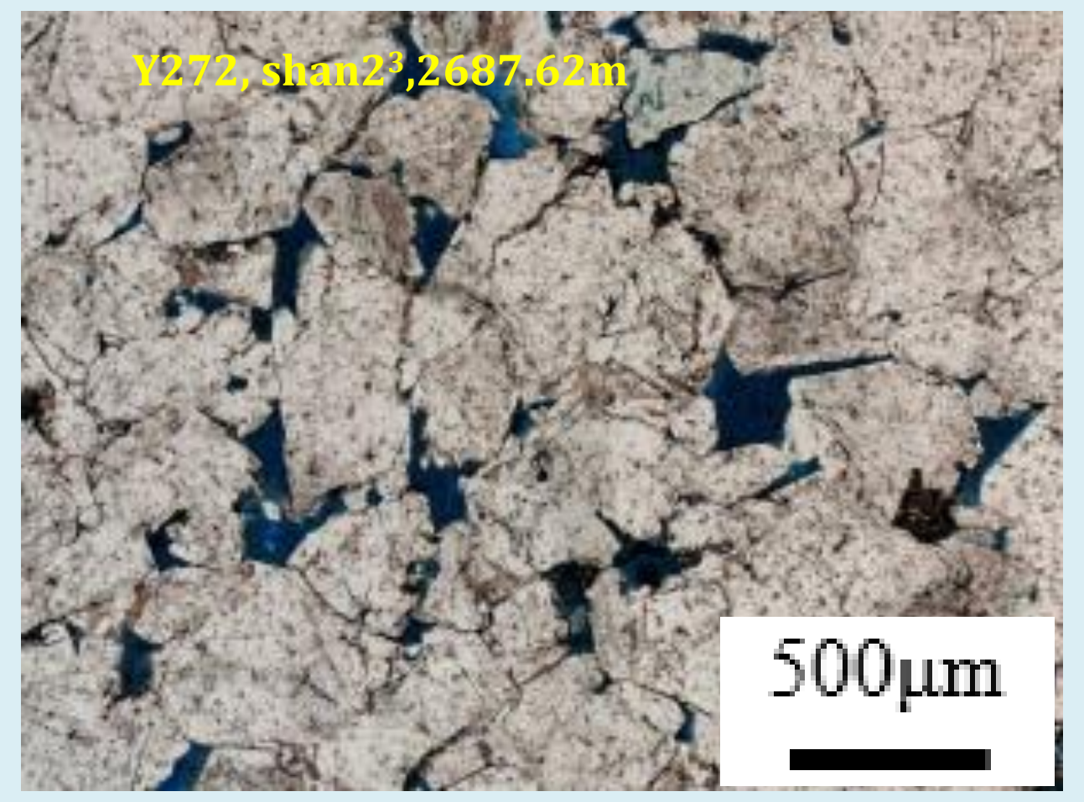
Saddle dolomite with undulating extinction, precipitating before quartz overgrowth



Kaolinite predating quartz cementation

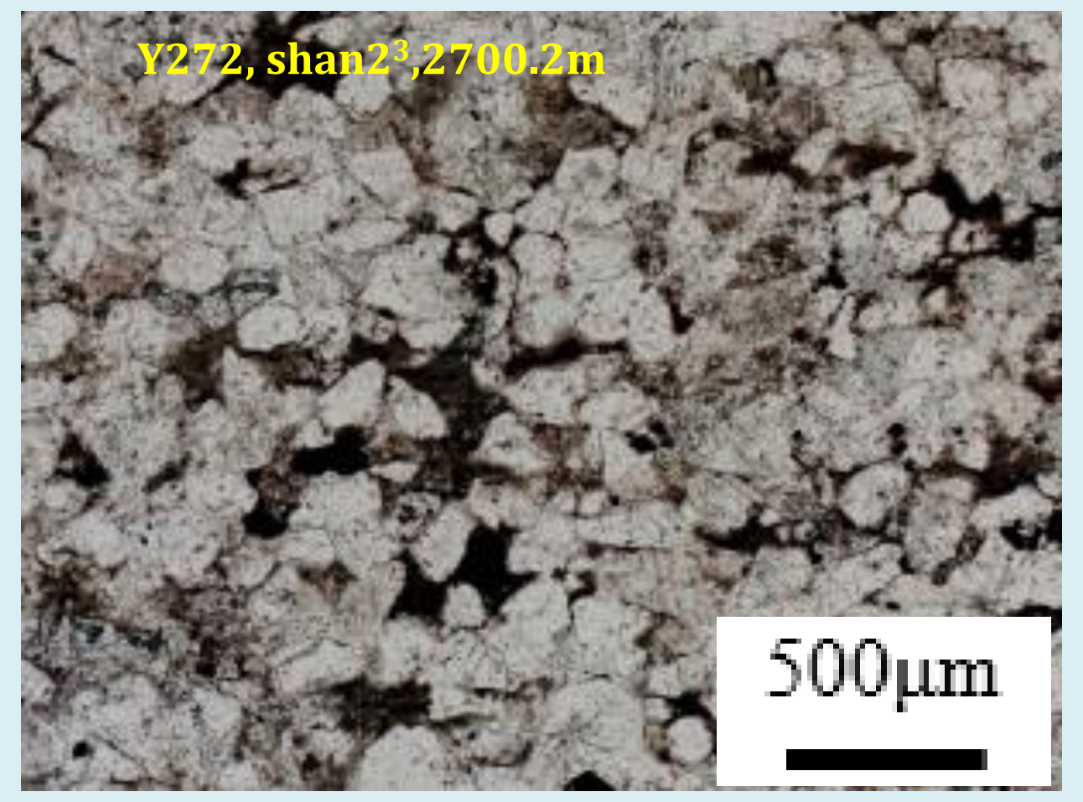
Multi-stage quartz overgrowth

SANDSTONE LITHOFACIES



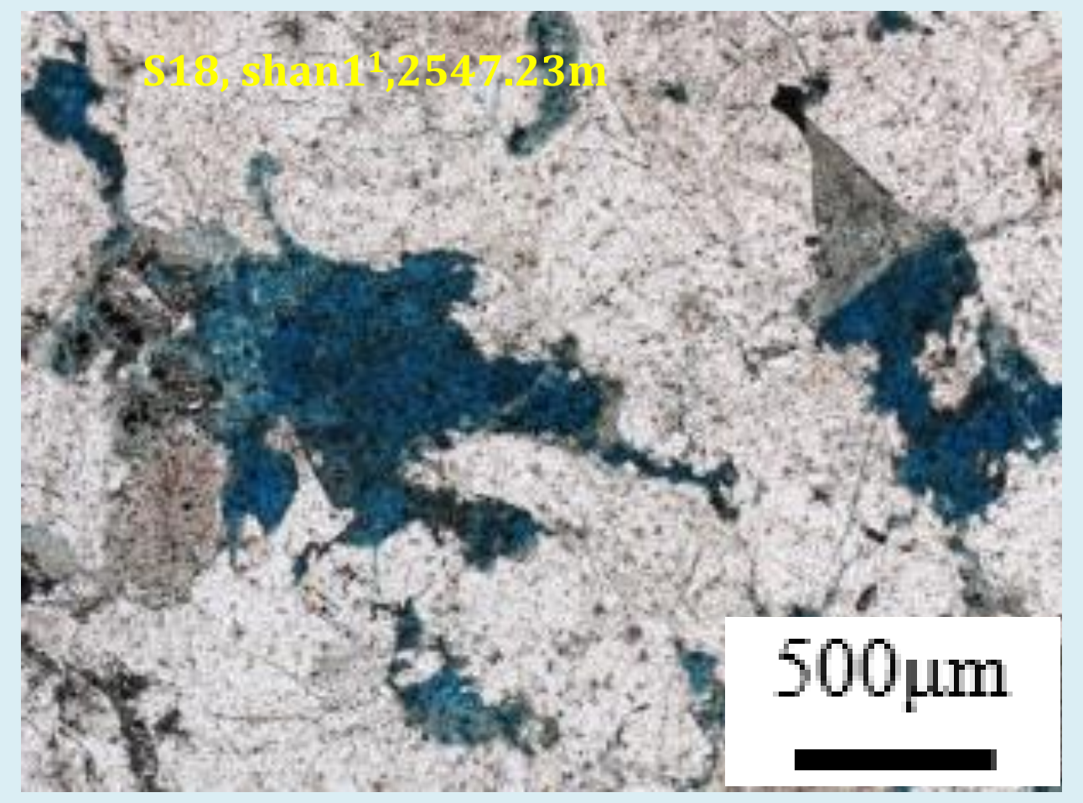
Lithofacies1: Quartzarenite

Reservoir facies, only present in Shan23, characterized by coarse- to medium-grained framework grains, wide varieties but lower total contents of authigenic minerals. Main porosity is primary intergrain with minor moldic porosity and kaolinite microporosity. Core plug porosity ranges from 5.4% to 11.7% and permeability between 0.113 and 83.000 mD.



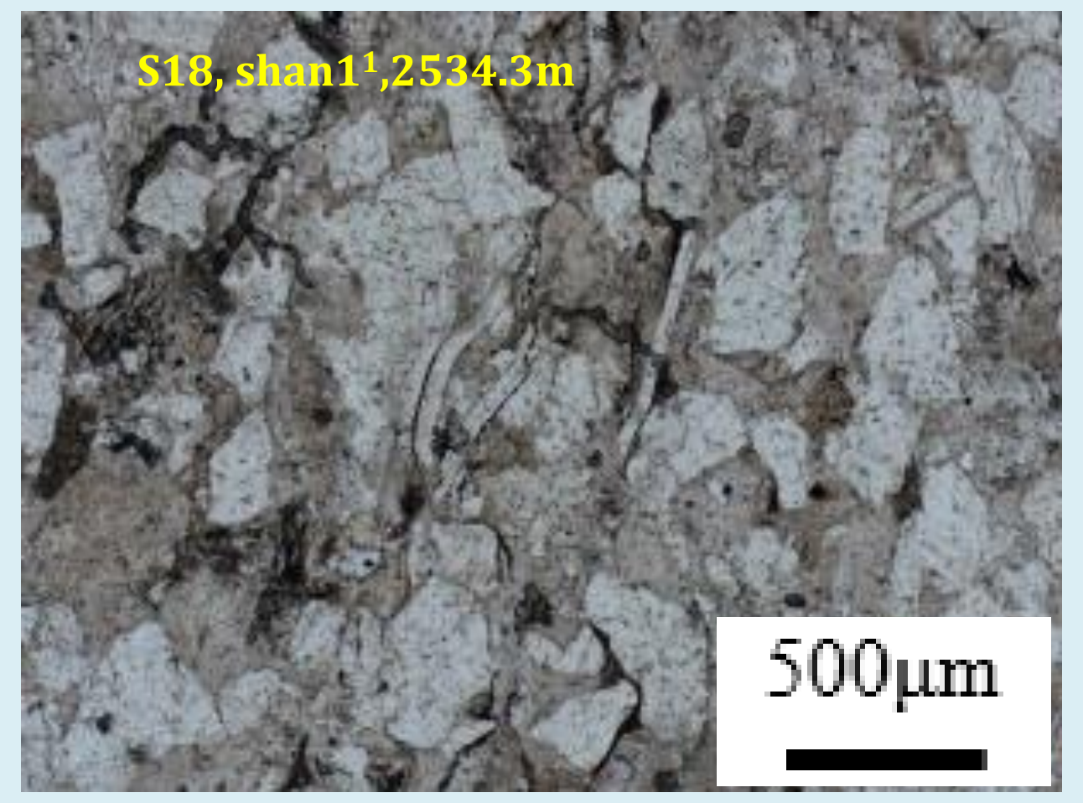
Lithofacies2: Tuffaceous quartz sandstone

Fine-grained sandstone containing abundant tuffaceous matrix (7%-26%), without thin porosity. Core porosity is less than 5%, permeability less than 0.1mD. Non-reservoir facies.



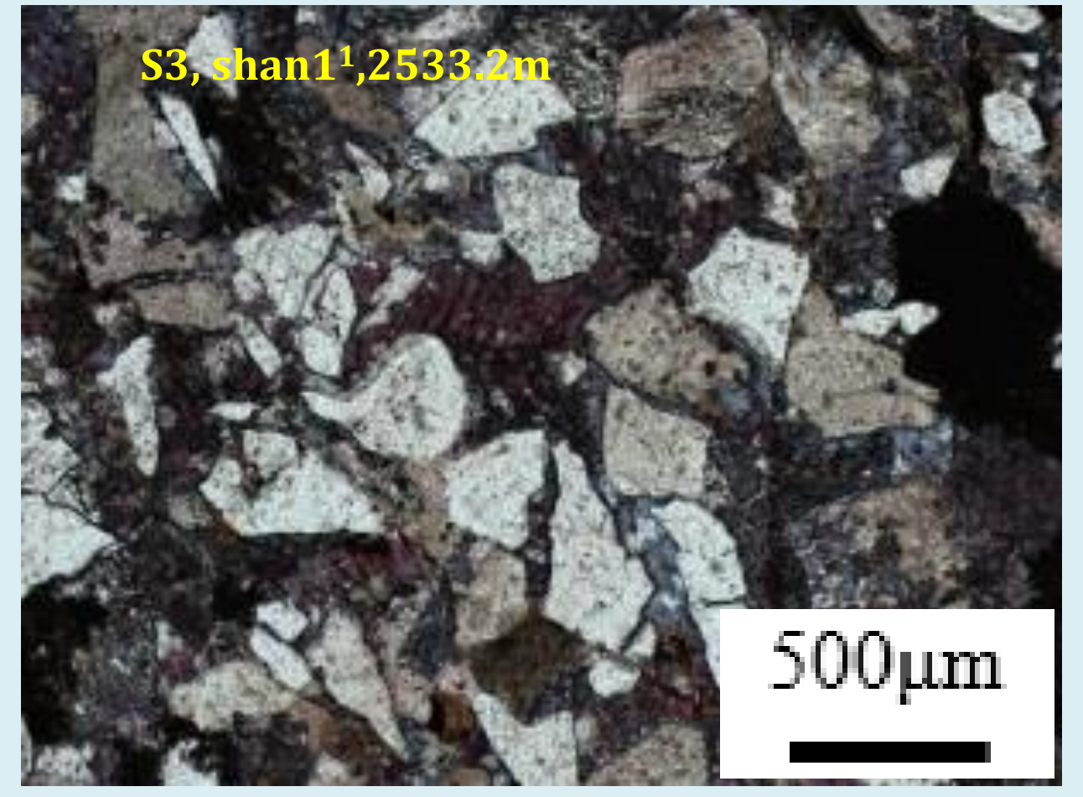
Lithofacies3: Ductile lithic-lean sublitharenite

Reservoir facies, occurring in Shan2$^{1-2}$and Shan1, characterized by coarse- to medium-grained detrial grains, wide kinds but lower total contents of cements. Thin porosity is a combination of intragrain dissolution porosity and kaolinite microporosity. Core porosity ranges from 4.7% to 11% and permeability between 0.050 and 6.421 mD.



Lithofacies4: Ductile lithic-rich sandstone

Coarse- to fine-grained litharenite and sublitharenite, characterized by abundant ductile lithic fragments and/or detrital clay matrix. The diagenesis is dominated by the ductile deformation of lithic fragments without thin porosity. Core porosity is less than 5%, permeability less than 0.1mD. They occur in Shan2$^{1-2}$and Shan1. Non-reservoir facies.

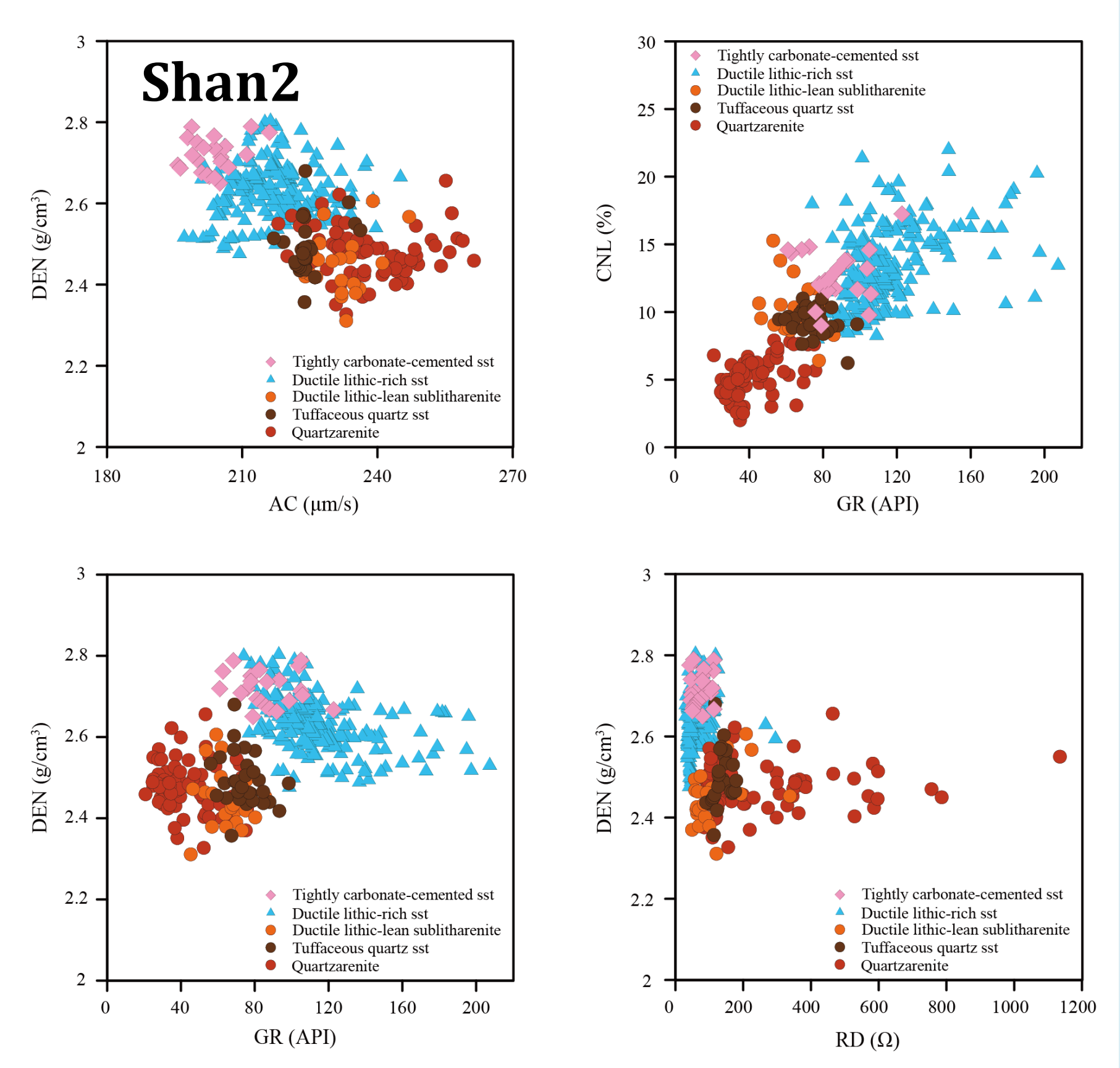


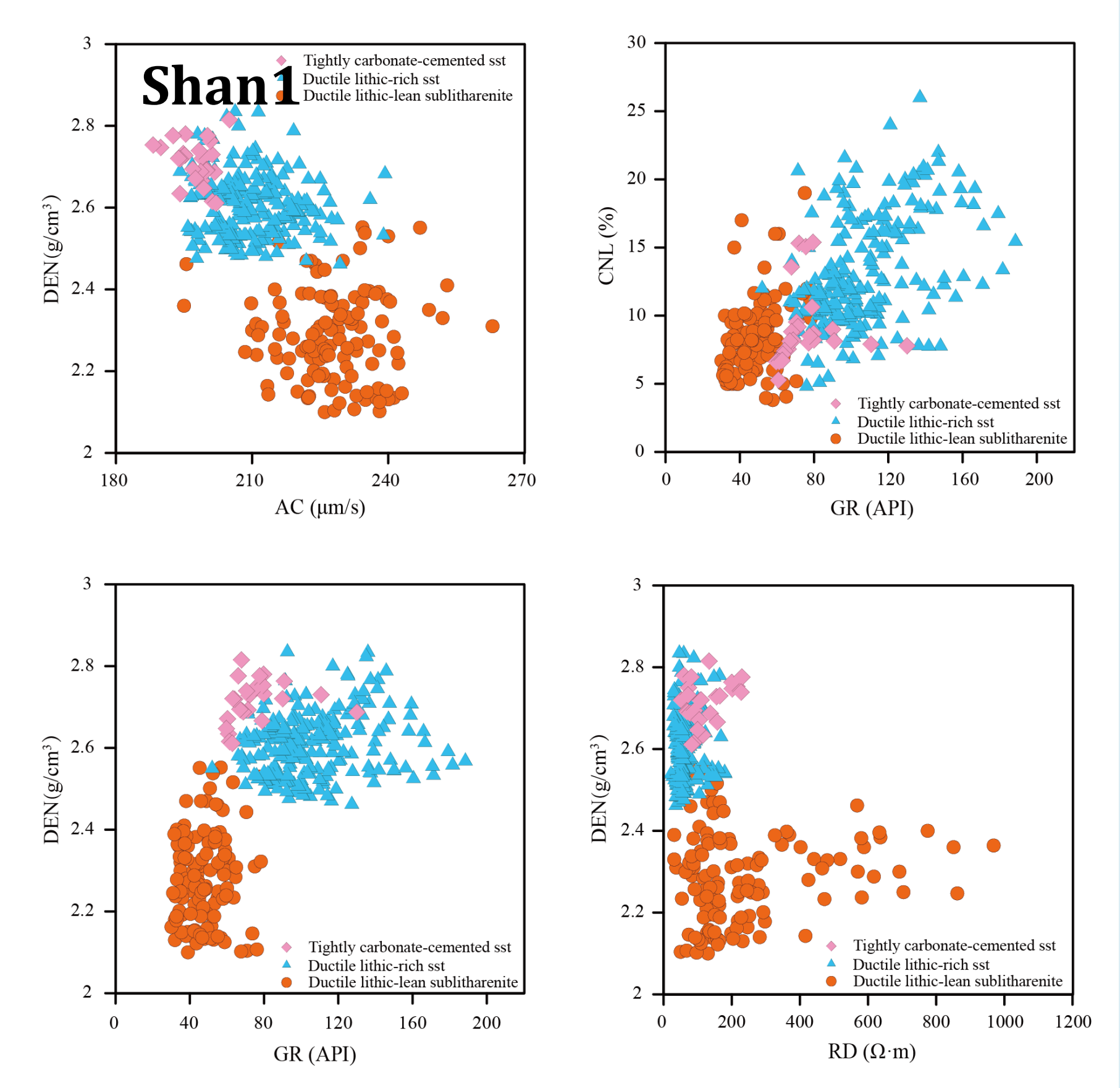
Lithofacies5: Tightly carbonate-cemented sandstone

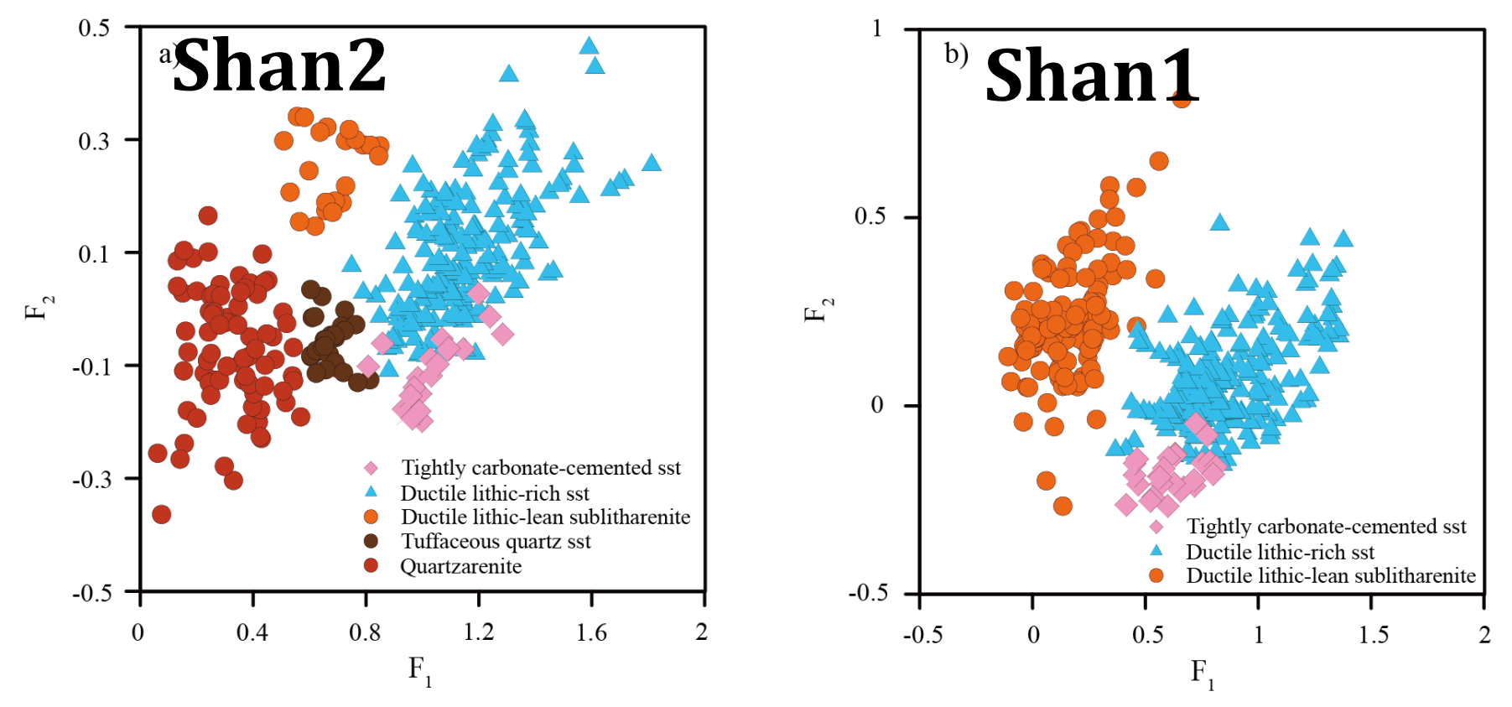
medium- to fine-grained litharenite and sublitharenite completely cemented by calcite and siderite. Core porosity is less than 5%, permeability less than 0.1mD. Non-reservoir facies.

PREDICTION MODEL OF LITHOFACIES USING WELL LOGS

Determined predictor variables include GR, AC, DEN, CNL, RD. Quartzarenites and Ductile lithic-lean sublitharenites feature low GR, CNL and DEN, and high AC and RD Values. Ductile lithic-rich sandstones are characterized by high GR, CNL and DEN, and low AC and RD values. Tightly carbonate-cemented intervals are identified by high DEN and low AC values. Note that bipolts of well logs are not very effective in identifying these lithofacies.







Crossplots of principal components distinguishing different lithofacies

Performance of lithofacies prediction model

Shan2

Actural lithofacies	Success (%)	Overlap1 (%)	Ovelap 2 (%)
Lithofacies 1	97	3	
Lithofacies 2	100	0	
Lithofacies 3	91	9	
Lithofacies 4	90	2	8
Lithofacies 5	78	9	13

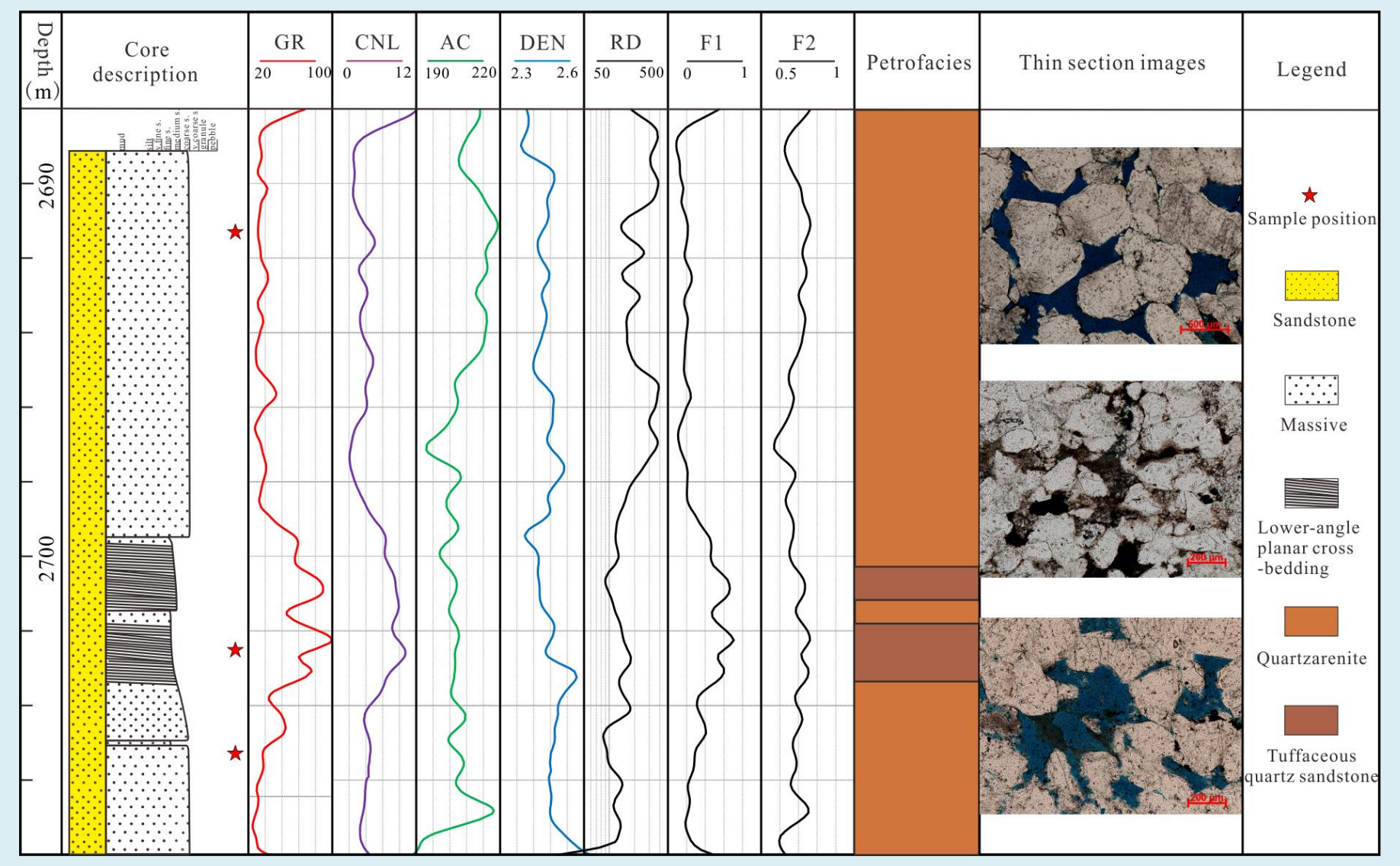
Shan1

Actural lithofacies	Success (%)	Overlap1 (%)	Ovelap 2 (%)
Lithofacies 3	97	3	0
Lithofacies 4	94	1	5
Lithofacies 5	88	8	4

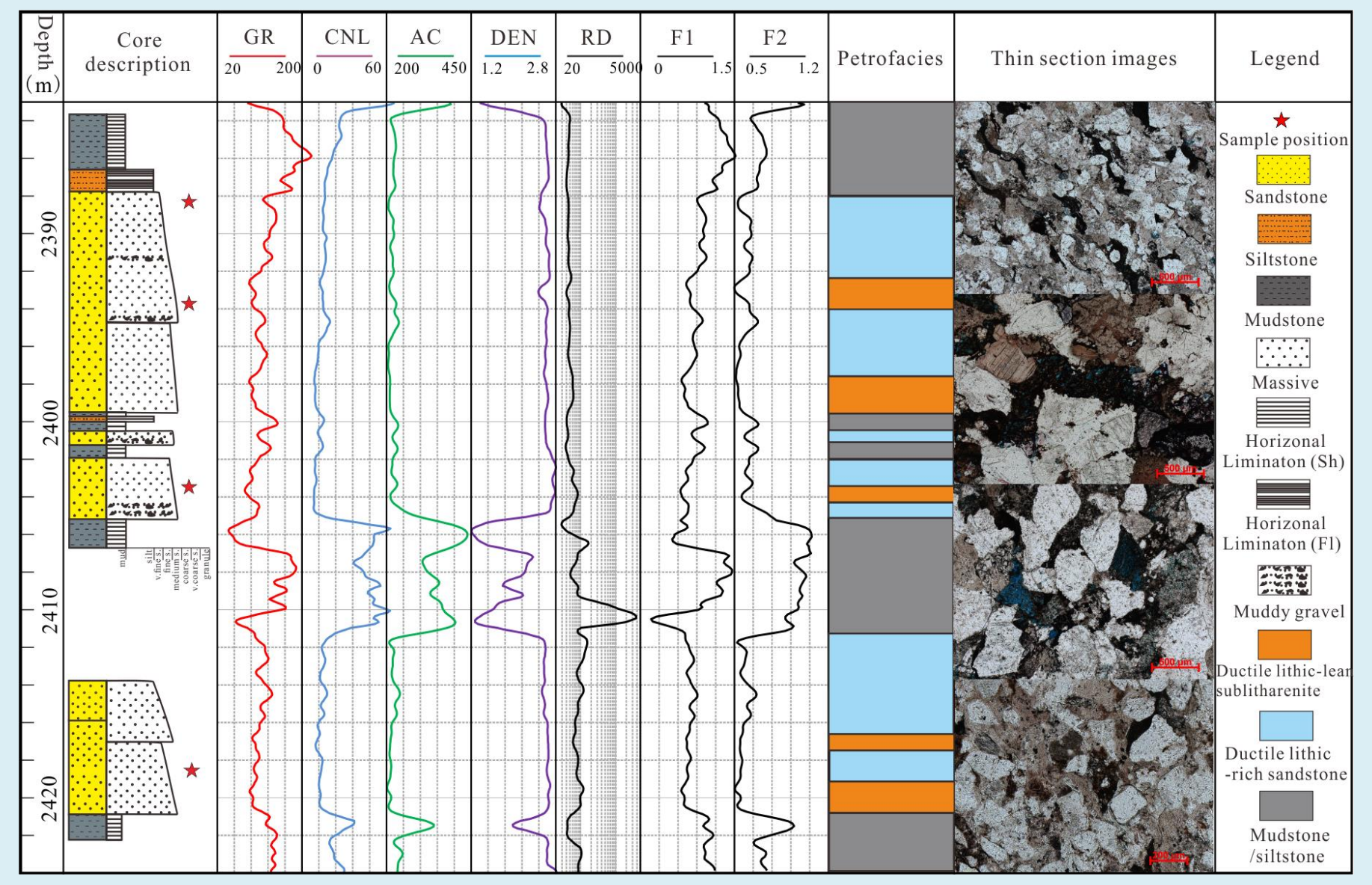
A model based on principal component analysis (PCA) show better identification of the five lithofacies than biplots of well logs.

A blind test has been performed to evaluate the validation of the model in well Yan272, Y100 and Y340, which is not used to build the model. The predicted lithofacies are corresponding with petrographic features of core samples.

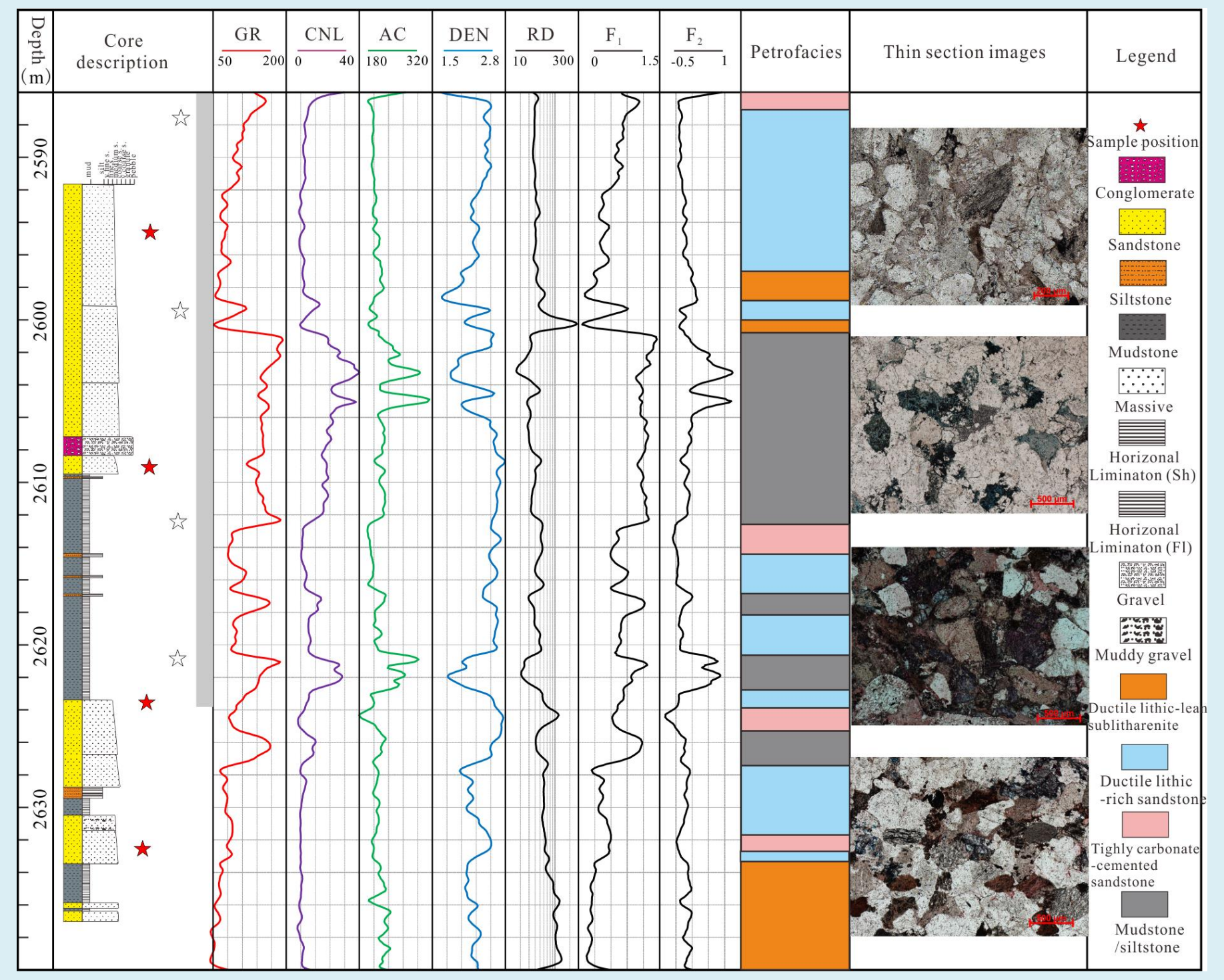
Validation of the model



Well Yan272 Shan2³



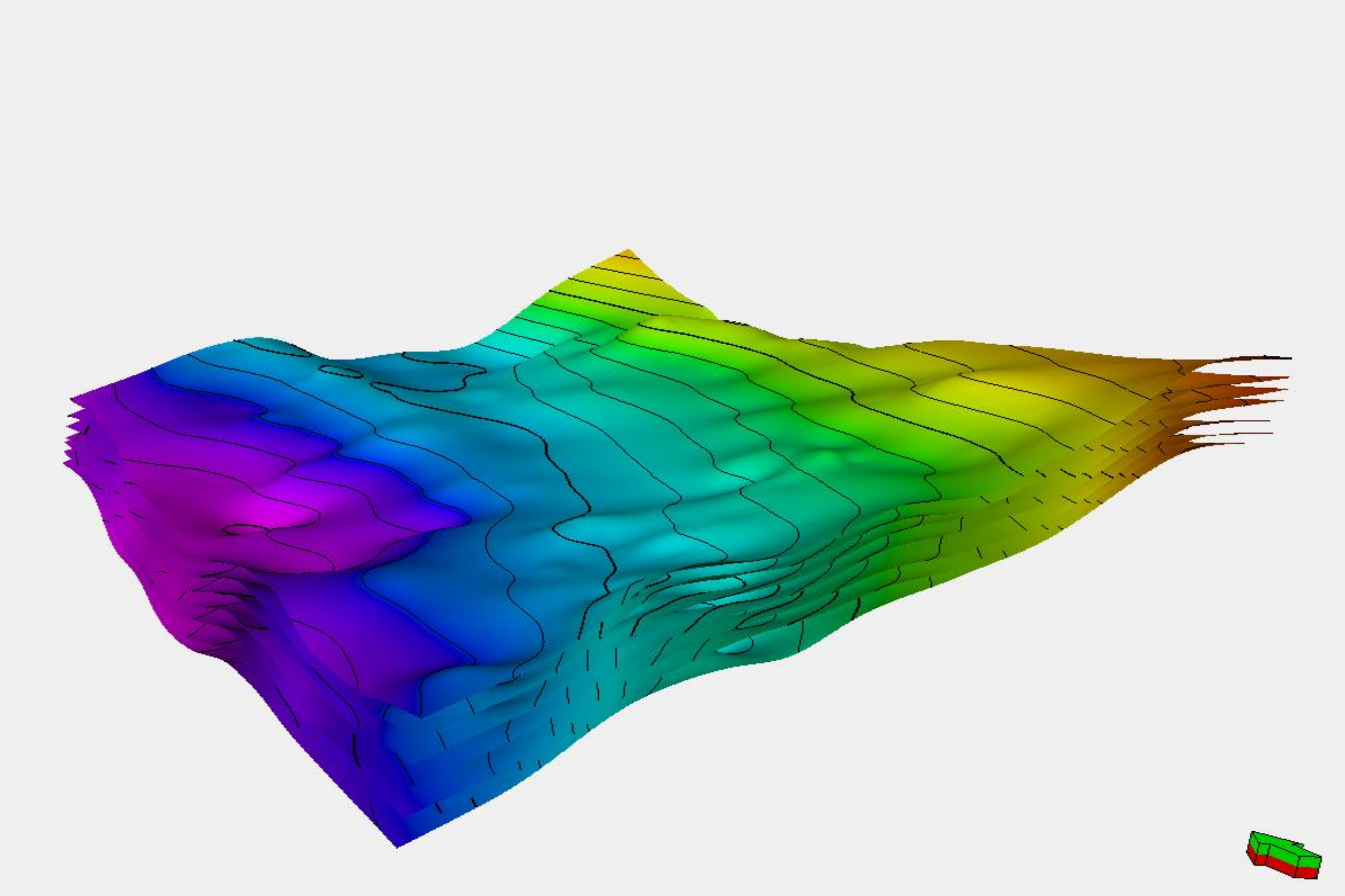
Well Yan110 Shan2$^{2-1}$

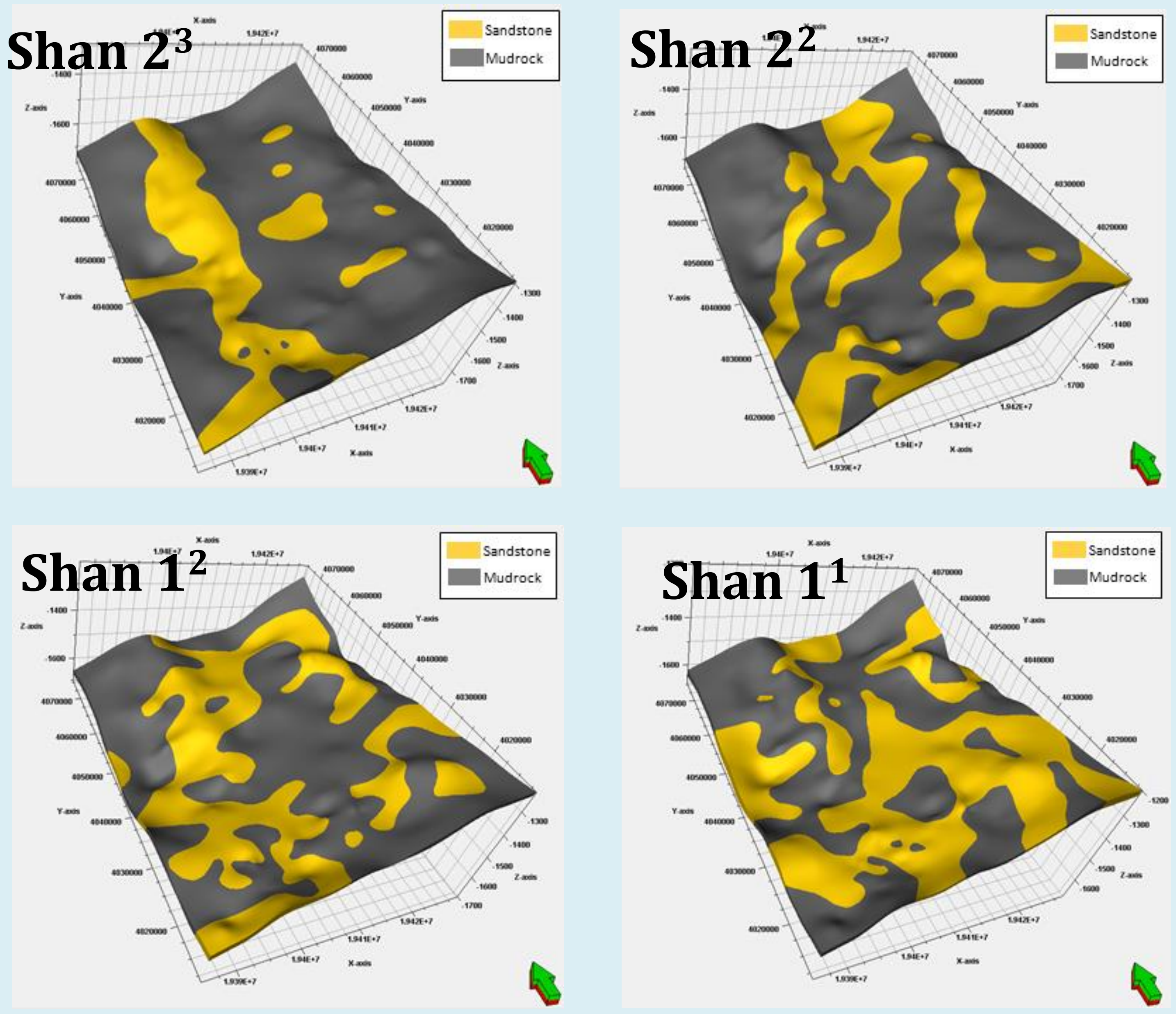


Well Yan340 Shan1

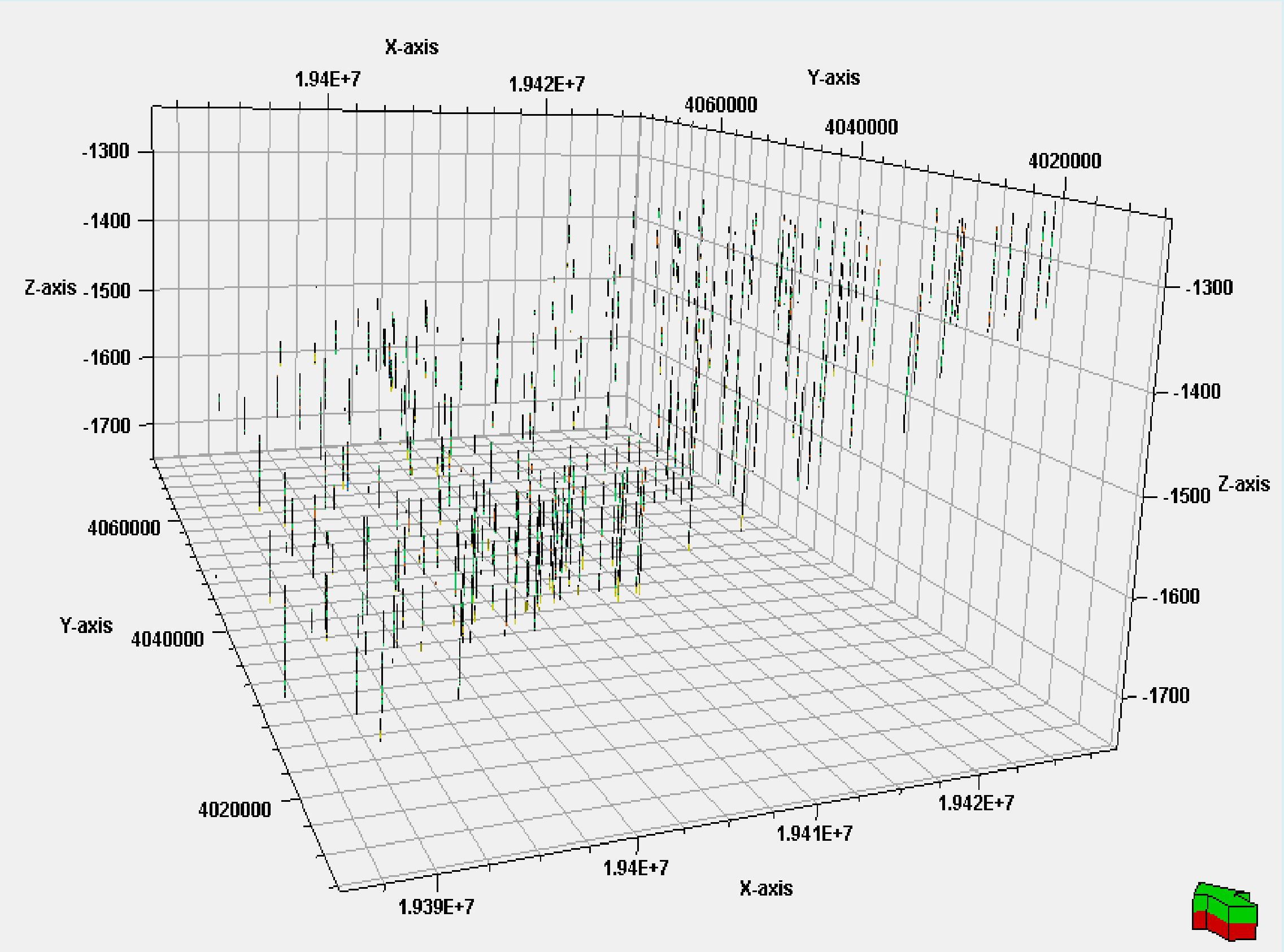
3-D GEOLOGICAL MODEL

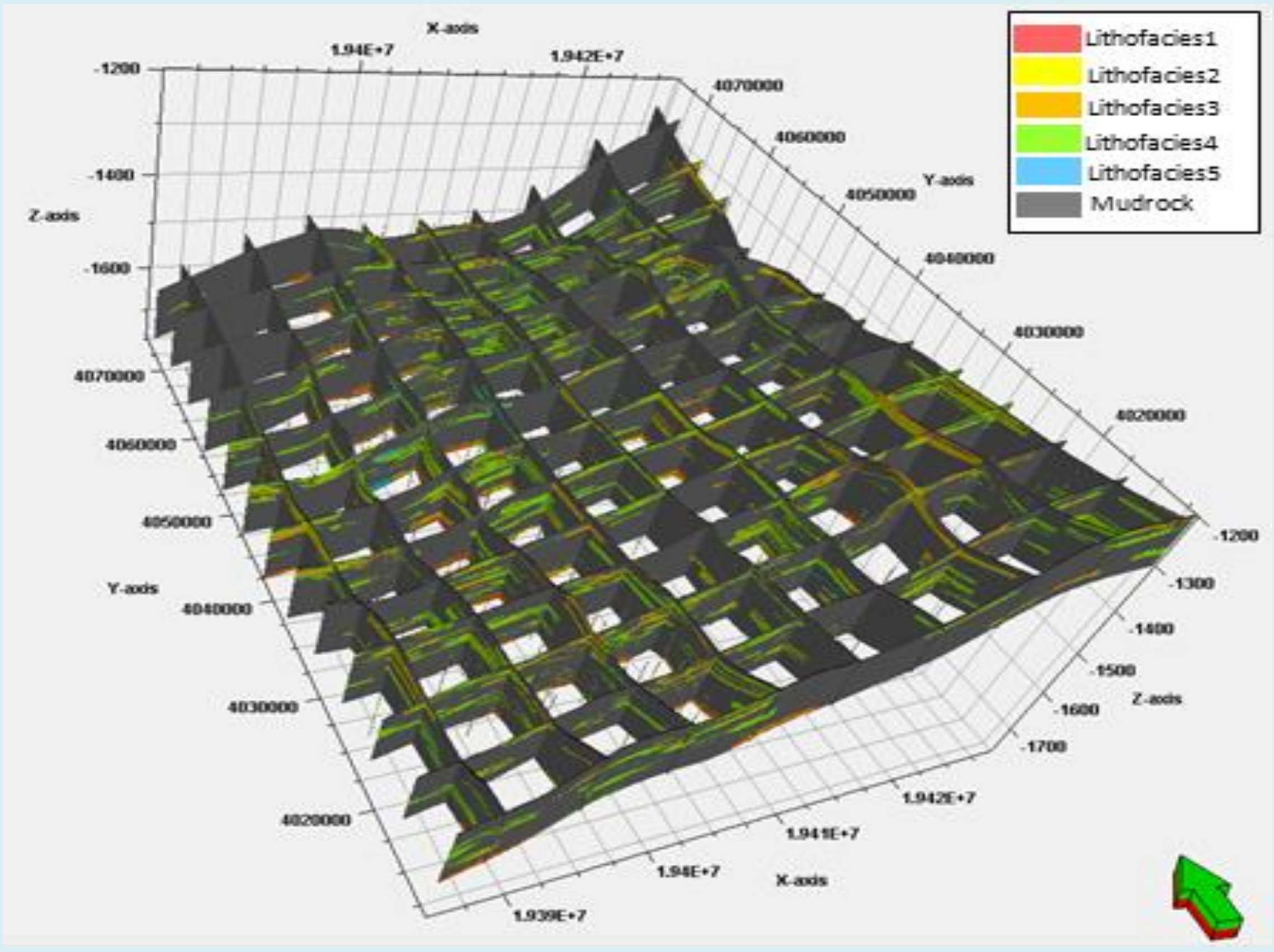
Structural modeling is the first step in building 3D model. The grid used is 50×50×0.5 m. building the zone of the reservoir (Shan 2^3, Shan2^2, Shan2^1, Shan 1^3, Shan1^2 and Shan1^1) in the model and then creating the laryer in the zone



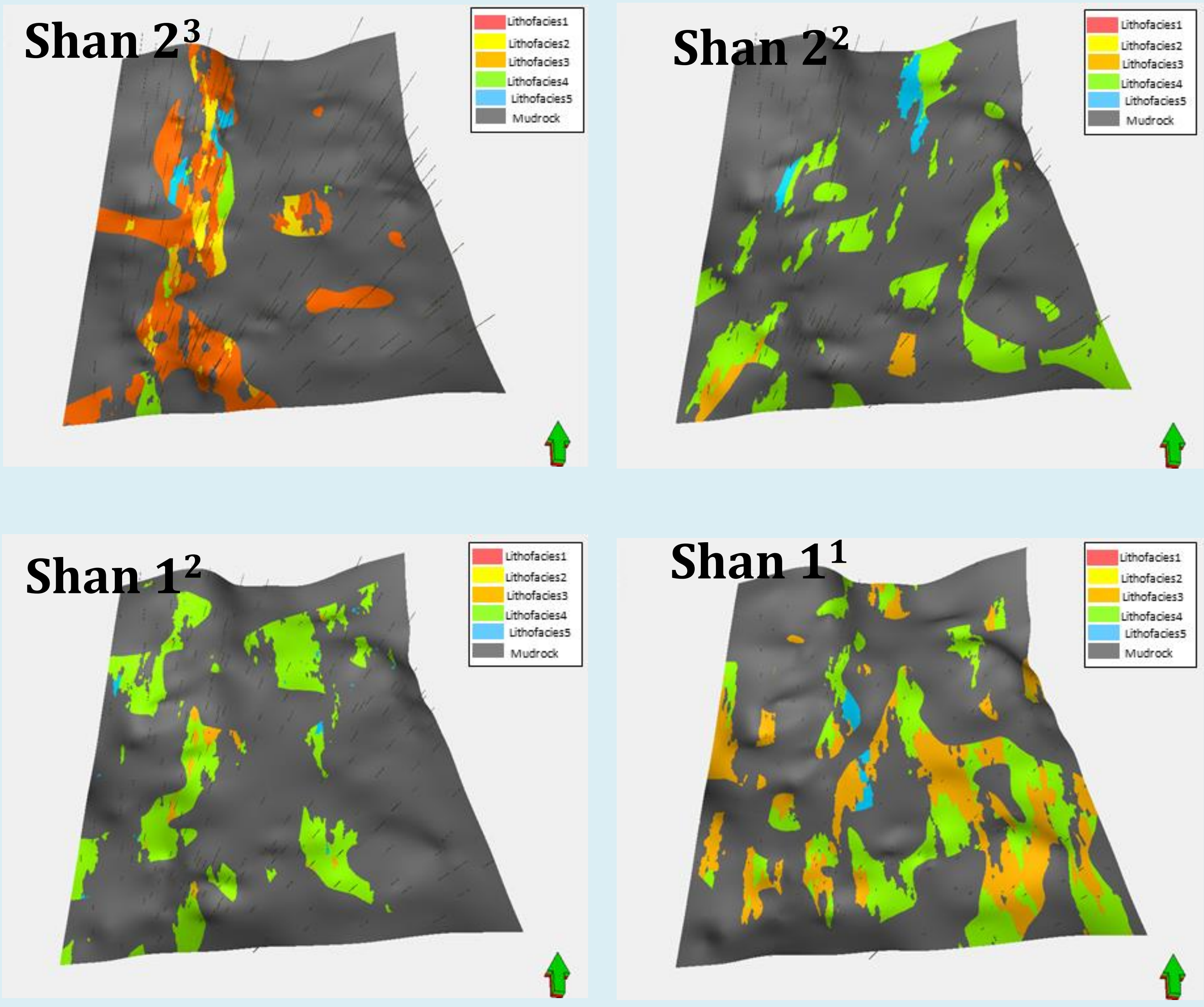


A 3D architectural model of channel-belt is constructed based on multiple evolutionary maps of regional depositional microfacies





Lithofacies are modeled further by interpreted well data using sequential Gaussian method.



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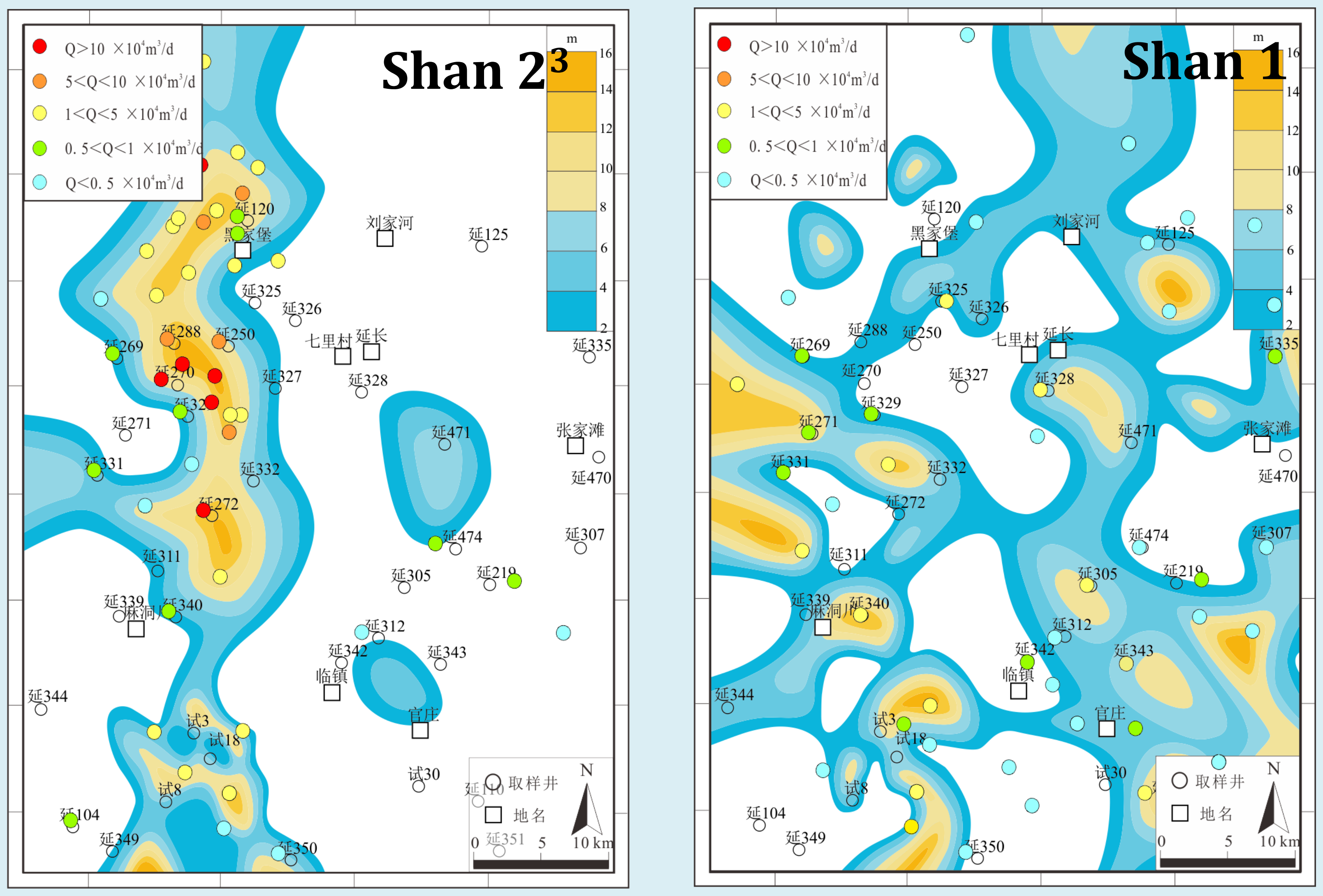

The prediction of high-quality sandstones is validated by correlation with gas production test, which suggests it is helpful predictive model

CONCLUSION

For strong heterogeneity in petrography and petrophysics of tight gas sand reservoirs, multiple scales of analyses from microscale, drill core to well logging have been conducted and five petrofacies have been defined in gas reservoirs.

A model based on principal component analysis has been constructed to predict high-quality rocks using well logs corrected from thin section and drill core data. The micro-scale description of petrofaceis has been upscaled to field-scale characterization by facies-controlled modeling technique and availability of tight gas sand reservoir has been quantitatively assessed.

Selected reference:

Ozkan A, Cumella S P, Milliken K L, Laubach,2011. Prediction of lithofacies and reservoir quality using well logs, Late Cretaceous Williams Fork Formation, Mamm Creek field, Piceance Basin, Colorado. AAPG Bulletin, 95(10): 1699-1723: