3-D Seismic Attribute Study For Reservoir Characterization Of Carbonate Buildups Using A Volume-Based Method

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ABSTRACT

Introduction And Geologic Overview

The Upper Jurassic (Oxfordian) Smackover Formation is a stratigraphically complex carbonate formation, and a major producer of hydrocarbons in the northeastern Gulf of Mexico (Baria *et al*., 1982; Salvador, 1991). The main reservoir facies in the Smackover Formation are the microbial reefs, which were formed in a gently sloping to distally steepened carbonate ramp depositional setting (Benson *et al*., 1996). Although several studies have been carried out to describe and characterize physical properties of the Smackover reservoir interval in the northeastern Gulf of Mexico, their heterogeneity resulting primarily from their stratigraphic complexity is yet to be properly defined (Baria *et al*, 1982; Benson *et al*., 1996; Mancini *et al*., 2000; Parcell, 2000; Hart and Balch, 2000).

In this study, we use a volume-based 3-D seismic attribute study to directly image rock physical properties (porosity) in the Smackover carbonate buildups of southwestern Alabama. Seismic attribute studies seek to find empirical correlations between seismic attributes and log-derived physical properties such as lithology, porosity, etc, through methods such as multivariate linear regression (MLR) and artificial or probabilistic neural networks (ANN/PNN; Schultz *et al.,* 1994a&b; Russell *et al*., 1997; Hampson *et al*., 2001). By examining images derived using this volume-based method, it may be possible to deduce relationships between the predicting attributes and features of the reservoir that were not readily apparent from using a single data type. Finally, we demonstrate the possibility of using multiattribute results to foster an understanding of depositionally oriented trends in porosity distribution that have been observed in these buildups.

The study area for this project encompasses Appleton Field (Fig. 1), a Smackover oil field of the basement ridge play in southwestern Alabama. Numerous studies have been carried out in an attempt to define the spatial distribution of depositional facies, the major factor controlling reservoir heterogeneity, and porosity within the Appleton Field (Mancini *et al*., 2000; Hart and Balch, 2000; Parcel, 2000). Facies heterogeneity and porosity need to be defined in 3-D space in order to optimize field production and development strategies.

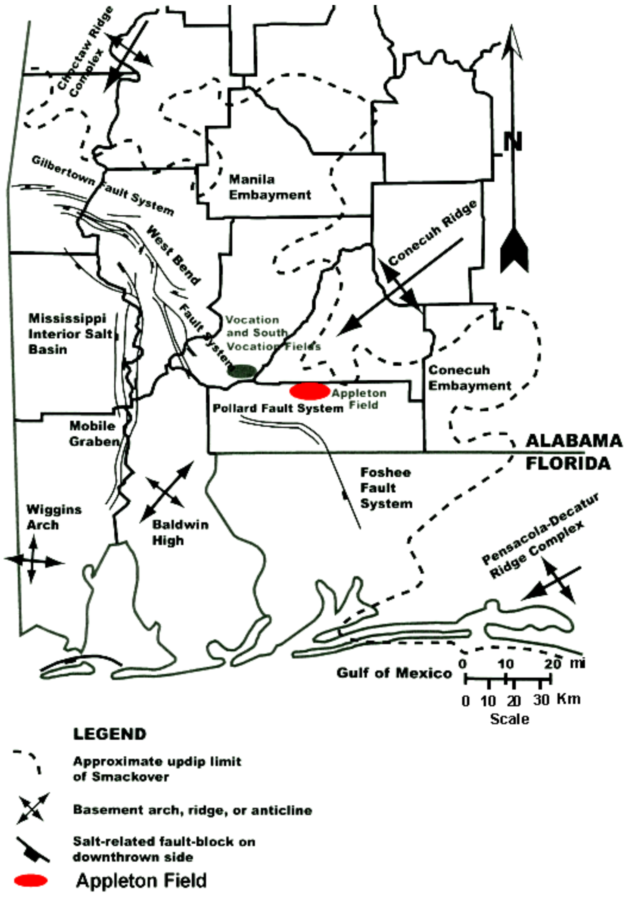


Fig. 1: Location Map of study area showing existing structural controls at time of Smackover deposition. Adapted from Mancini (2002, Fig. 1).

Database And Methodology

Sonic logs of 11 were used to generate synthetic seismograms in order to calibrate log and seismic data (Fig. 2). Six of these were chosen for multiattribute analyses. The subset of seismic data used consisted of an approximately 5 x 3.5 km grid of a post-stack, time-migrated 3-D volume, with a bin spacing of 165 x 165 ft (~50 x 50 m), and a 4 second two-way travel time (TWT) trace length.

A data-driven approach was used as described by Schultz *et al.,* (1994) and Hampson et al. (2001). A volume-based method using both multiattribute step-wise linear regression (MLR) and probabilistic neural network (PNN) statistical techniques has been adopted due to the thickness (Fig. 3; 80 - 230ft / 24 - 70m) and stratigraphic complexity (rapid facies changes) of this formation (*c.f.* Russell *et al.,* 1997; Hampson *et al.,* 2001).

A probabilistic neural network was trained using the same set of predicting attributes derived from MLR to improve the quality of fit. This is because PNN is a pattern recognition tool (*c.f.* Liu and Liu, 1998) and so may better capture non-linear relationships between the attributes and log porosity than MLR. Exclusion testing was carried out to test the effectiveness of the statistical relationship in areas of sparse well control.

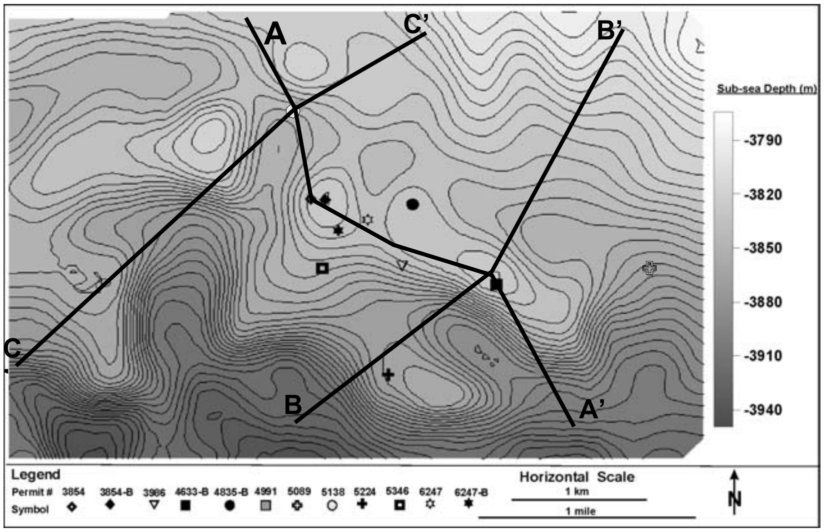


Fig. 2: Seismic grid showing the area covered by the current study and well locations. Transects A - A', B - B', and C – C' are also shown.

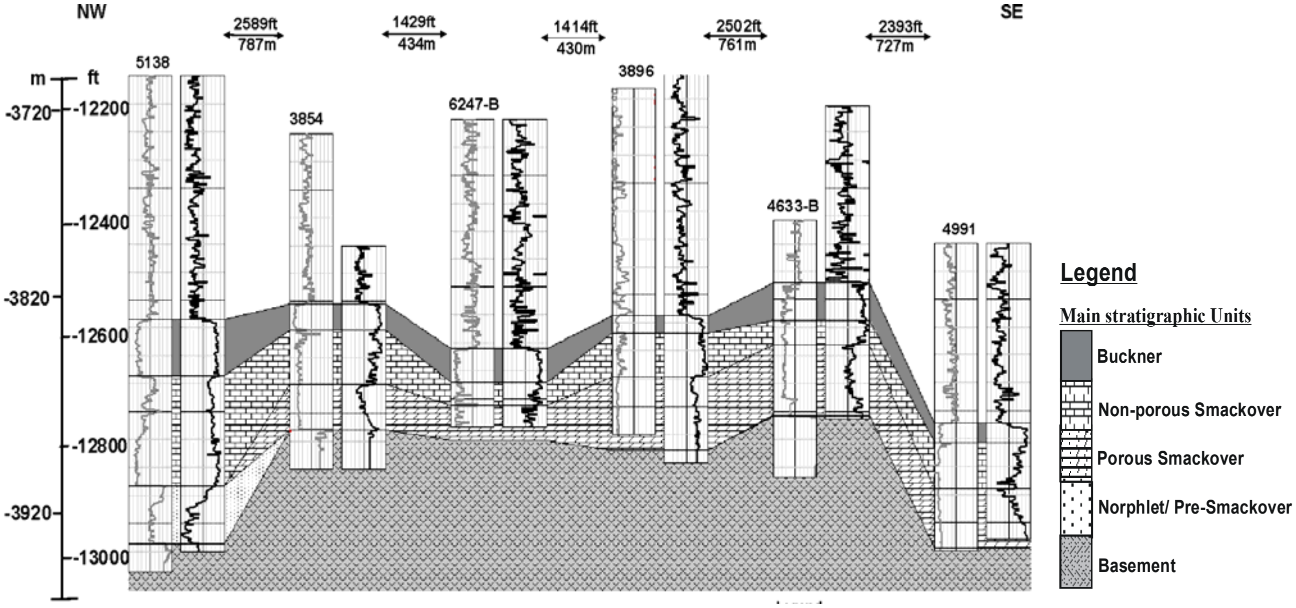


Fig 3: NW-SE well-to-well cross-section showing major stratigraphic units and their relationships. Cross-section was obtained along strike of paleohighs (A-A' transect of Fig. 2). Note that the eastern paleohigh at well 4633-B is structurally higher than that in the west beneath well 3854. Also, the porous unit of the Smackover is located preferentially on the paleohighs. Grey curve = gamma ray, black curve = sonic.

Results And Interpretation

The all-attribute validation plot (Fig. 4) indicated that four (Table 1) of the nineteen attributes trained represent the optimum number of attributes required to predict porosity. PNN was found to model porosity better than the MLR (Fig. 5).

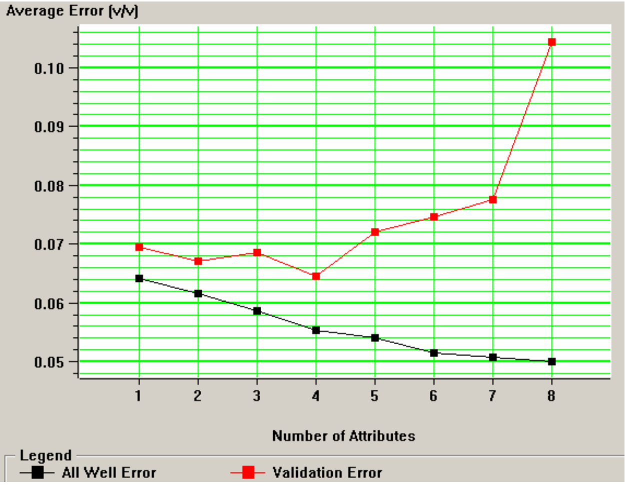


Fig. 4: Validation plot, showing the optimum number of attributes to use in predicting porosity from density porosity logs using stepwise multilinear regression. This optimum number of attributes is reached when the validation error (red curve) fails to decrease convincingly. The black curve shows the training error. The training error generally decreases with an increase in number of attributes.

Table 1: Ranked predicting attributes, weights applied to empirical relationships and their observed relationship to porosity changes in the Smackover Formation at the Appleton Field.

Seismic Attribute	**MLR Weights**	**PNN Sigmas**	**Relationship to Porosity**
Derivative	5.26796e-006	0.2127	Shows the onset and variation of energy for the Porous Smackover unit (Chen & Sidney, 1997). Correlated strongly to changes in the magnitude of acoustic impedance contrast across the Porous Smackover.
Derivative Reflection Strength	5.42256e-005	0.1725	Shows variations in lithology, stratigraphy, and thickness (Chen & Sidney, 1997; Taner, 1979, 1997). Major change observed resulted from thickness variation of the porous unit
Cosine Instantaneous Phase	-0.0467525	0.4096	Generates a better display of phase variations (Chen and Sidney, 1997; Taner, 1997; Yilmaz, 2001). Defined precisely the lateral extent and stratigraphic configuration of the whole Porous Smackover unit.
1/Smooth Inversion Results	10263.8	0.3773	Shows the acoustic impedance structure (Yilmaz, 2001). Serves as a good indicator of porosity within the Porous Smackover.
Constant	-0.117512	0.4625	None

From examining sections through both the PNN-derived porosity volume (Fig. 6), porosity is generally higher on the forereef flanks than the crests of paleohighs.

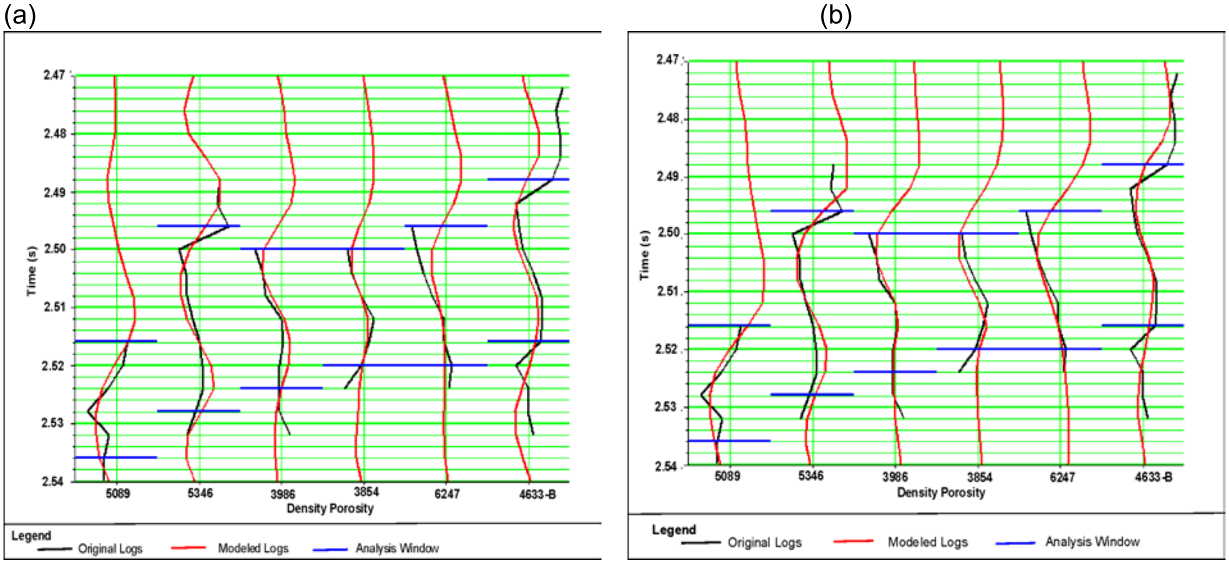
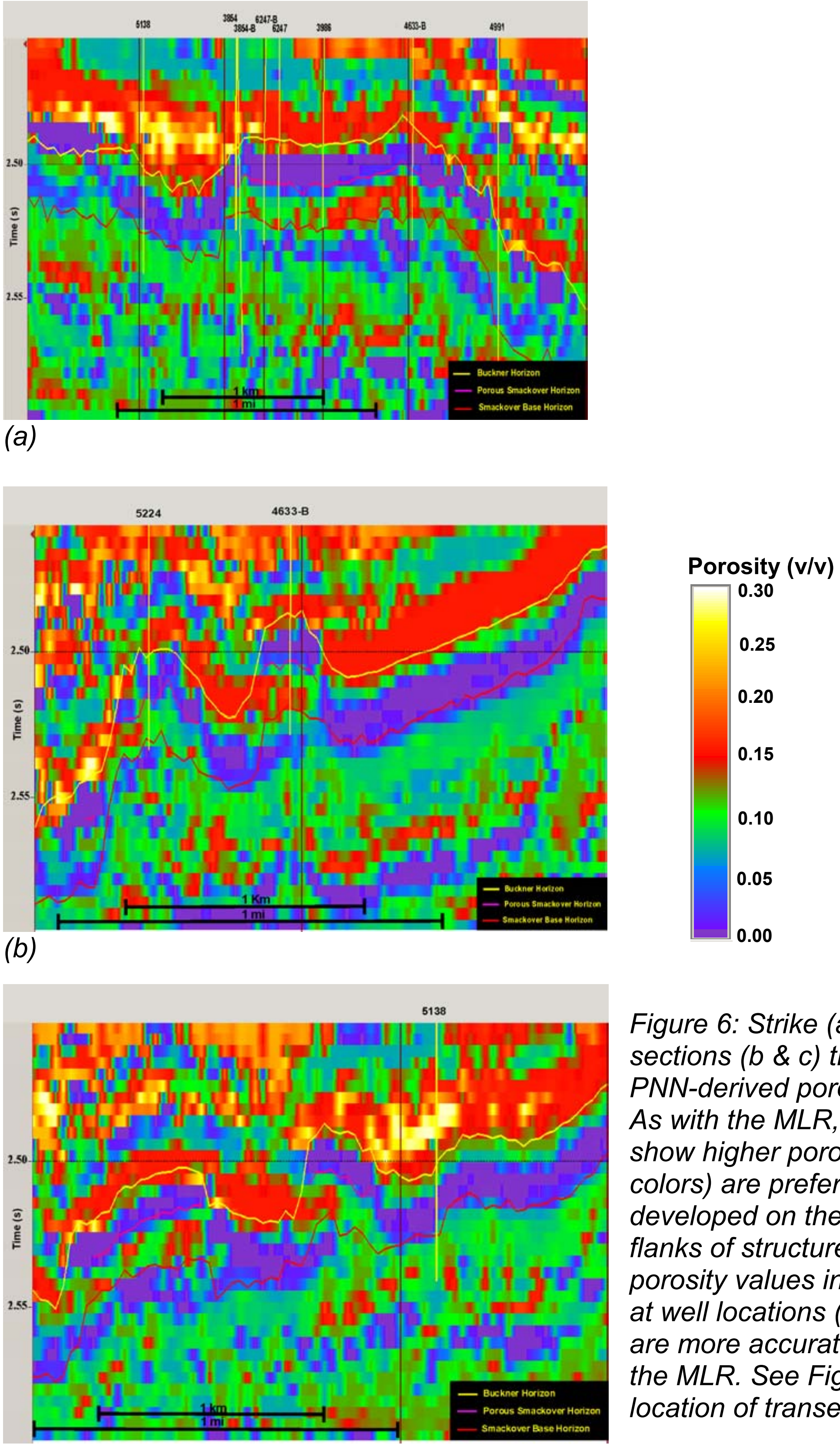


Fig. 5: Visual correlation of actual and modeled/predicted porosity on application of multiattribute equation derived from (a) MLR and (b) PNN. Correlation is only valid in interval defined by analysis window (blue lines). Porosity increases to the right of the curve. Note how well PNN models porosity.



(a)

(b)

(c)

Figure 6: Strike (a) and dip sections (b & c) through the PNN-derived porosity volume. As with the MLR, all sections show higher porosities (hot colors) are preferentially developed on the seaward flanks of structure. The porosity values in this volume at well locations (e.g. 5224) are more accurate than with the MLR. See Figure 2 for location of transects.

Slices at 4 ms intervals through the reefal interval of the PNN volume (Fig. 7), also highlight the general trend of higher porosities occurring along the southern flanks than the crests of the structure.

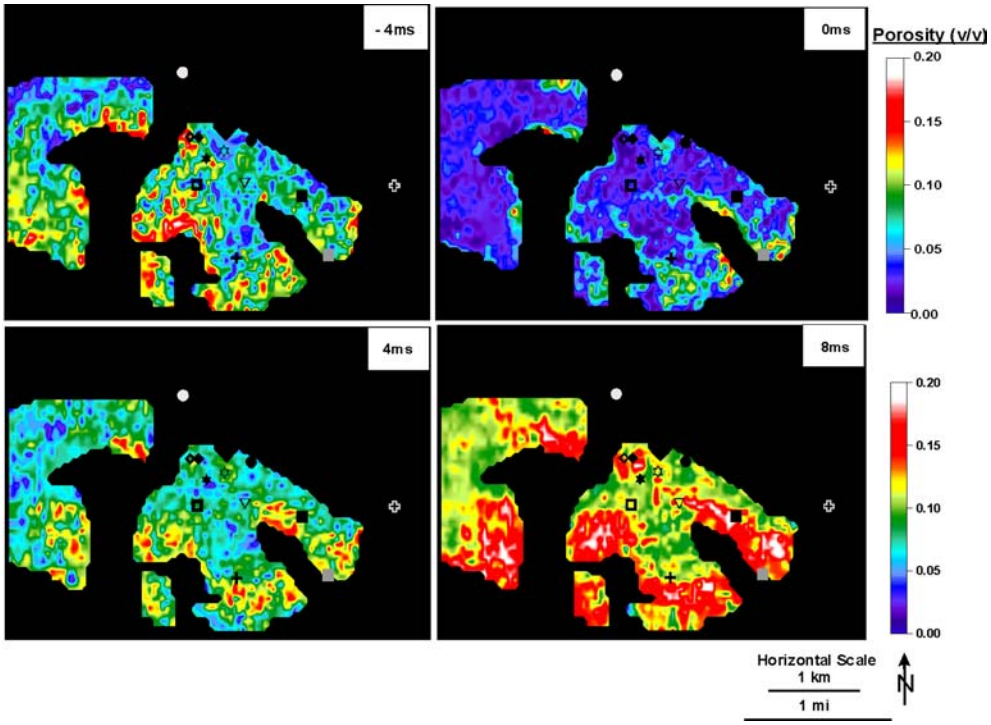


Fig. 7: Slices through the porosity volume (porosity values are in decimals (v/v) i.e., volume of voids/total volume of rock), starting 4 ms above the porous Smackover pick. Porosity at –4 ms above this pick was attributed to shoal grainstone facies, which constitute the other major reservoir facies in the Appleton Field. Note the overall association of higher porosities (hot colors) with the southern (paleoseaward) flanks of structure, which we attribute primarily to changes in facies type and growth form. Well symbols are indicated in Figure 2.

To better quantify the association of porosity development and paleostructure, a porosity thickness (Øh*)* map was constructed for the Smackover Formation using the PNN result (Fig. 8). This map shows the preferential development of porosity on the forereef flanks rather than on the crest of structure. The PNN map is geologically realistic given the facies types and their growth forms described from core studies (Table 2).

Preferential growth of reservoir grade facies on paleohighs in this and other basement play fields has been attributed to favorable substrate provided by the basement paleohighs, relative fluctuations of sea level, and carbonate productivity (Benson *et al.,* 1996). The overall effect of relative sea level variation is a change in character of the resulting buildups, manifested by the growth form, fabric, and as well as by later diagenetic alteration of the deposited lithofacies formed during changing sea levels. These changes in character have been described from log and core studies by Benson *et al.,* (1996), Parcell (2000), and Mancini and Parcell (2001), and are the main factors influencing reservoir formation, architecture and observed heterogeneity in this field. Compositionally, the buildups of the Appleton Field are mainly thrombolitic (Parcell, 2000; Mancini and Parcell, 2001). Growth of this algal morphology is favored by low background sedimentation, low oxygen, and high nutrient concentrations, conditions observed mainly during rising sea levels (Leinfelder, 1993). Each of the thrombolitic growth forms has significantly different physical characteristics (see Table 2) resulting primarily from their depositional fabric; as a consequence, they all have different reservoir quality. The thicker porosity in the forereef environment in this field, as opposed to other reef environments, is credited to the low background sedimentation and low to moderate energy, which enhanced the proliferation of deeper water dendroid thrombolites (Leinfelder, 1993; Parcell, 2000; Mancini and Parcell, 2001). Furthermore, early cementation that is pervasive due to greater water influx, aids against compaction and also influences the reef form (Tucker and Wright, 1990). In addition, the greater accommodation space created during sea-level highstand permitted these build-ups to grow to heights >100ft (30m).

Pervasive dolomitization of these facies has failed to obliterate original primary shelter and interparticle porosity resulting from facies growth form. It has improved facies porosity by stabilizing against burial compaction, created secondary porosity by dissolution, and increased permeability by enlarging pore throats. The predominance of the more porous thrombolitic facies on the forereef environment might also explain the strong water drive observed in reservoirs at the Appleton Field.

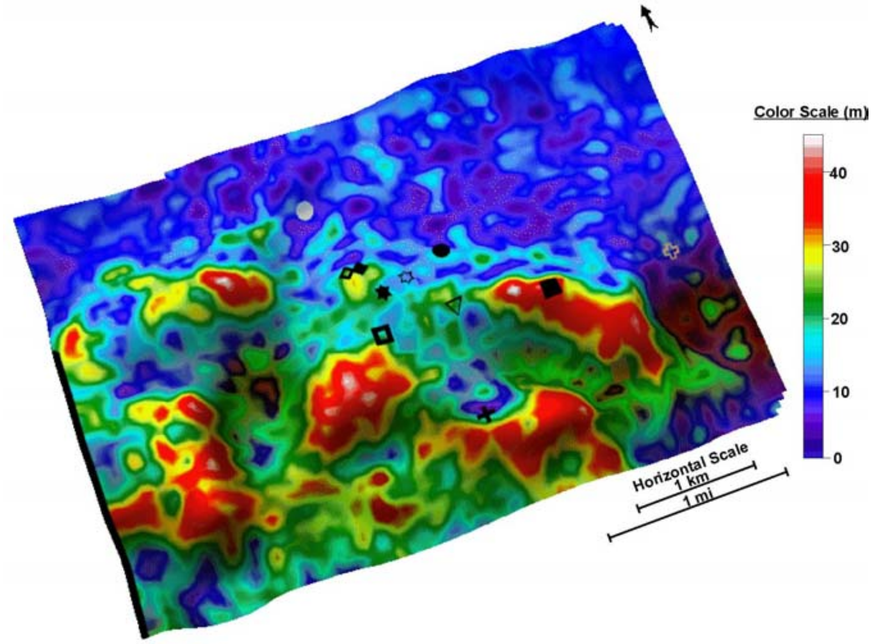


Fig. 8: Porosity thickness map of the Smackover Formation overlain on the Buckner/Smackover structure map for better display. Note the overall porosity thickness (hot colors) on the southern flanks of structure. Observed differences in the distribution of porosity is mainly a result of the non-linear relationship between the predicting attributes and the seismic data. Well symbols are indicated in Figure 2.

Table 2: Reef type, depositional fabric/growth forms, and their reservoir characteristics observed at the Appleton Field, SW Alabama. (Modified from Parcell, 2000)

Reef type	**Depositional fabric/growth form (wave energy)**	**Reservoir characteristics at Appleton Field**
Type I	Layered thrombolites (higher energy)	Good reservoir, lateral permeability
Type II	Reticulate/Chaotic thrombolites (moderate energy)	Good reservoir, lateral-vertical permeability
Type III	Dendroid thrombolites (lower energy)	Best reservoir, vertical permeability
Type IV	Isolated stromatolitic crusts (moderate energy)	Poor reservoir, low permeability
Type V	Oncoidal packstone/ Grainstone (higher energy)	Poor reservoir, low permeability (better if primary fabric is not occluded)

Conclusions

- This study demonstrates the effectiveness of seismic attribute studies to resolve problems involving reservoir characterization.
- The observed trend of increasing porosity and porosity thickness to the seaward flanks of paleostructure can be related directly to the growth forms and characteristics of the reservoir facies.

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