Seismic response to paleo-sand dunes in the Nugget Sandstone Formation, southwestern Wyoming

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Abstract

We have analyzed a 3D seismic survey acquired for a carbon sequestration project on top of the Moxa Arch in southwestern Wyoming. We observed a zone of discontinuous reflectors on vertical slices of seismic amplitude volume, whereas, the northwest–southeast lineations were observed on the time slices. We performed a seismic to well tie that suggested that the lineations occur within the Nugget Sandstone. The Nugget Sandstone is an eolian sandstone deposit of Early Jurassic age, deposited as a subtropical dune field, and equivalent to the Navajo Sandstone of southwestern Utah. Petrophysical analysis indicates that the Nugget Sandstone is dominated by clean sandstone (70%–80%), whereas evaporites, including halite and anhydrite, are present in certain zones. Previous outcrop studies on the Navajo Sandstone indicate the wind direction to be predominantly northeast–southwest. Seismic attributes, including coherence and curvature, displayed on stratal slices within the Nugget Sandstone interval indicate the presence of lineations in the northwest–southeast direction with irregular spacing. These lineations are approximately perpendicular to the inferred dominant wind direction. We computed the dominant wind direction from the average azimuth of the lineations as seen on the curvature attribute in the Nugget Sandstone interval.

Geological feature: Eolian sand dunes with interdunal evaporites

Seismic appearance: Parallel lineations with irregular spacing on seismic attribute horizon slices

Alternative interpretations: Canyons at continental slopes; slope failures

Features with a similar appearance: Marine bars; contourites

Formation: The Nugget Sandstone — equivalent to the Navajo Sandstone

Age: Early Jurassic

Location: Moxa Arch, Wyoming

Seismic data: Obtained by the University of Wyoming with US DOE funding

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Analysis tools: Coherence and curvature attributes; seismic inversion; petrophysical inversion

Paleo-wind direction and modern analogue

Previous studies, including those of Parrish and Peterson (1988), Chan and Archer (2000), Loope and Rowe (2003), have mentioned sand dunes in the Navajo Sandstone, the equivalent of the Nugget Sandstone in Utah and Arizona. The paleo-wind direction was inferred from outcrops in these areas, by measuring strikes and dips and by drawing dipoles that indicate the corresponding wind direction for each of these localities. After calculating the average azimuth of these dipoles, the dominant paleo-wind direction was determined and is represented by the blue arrows in Figure 1a. Our study arrives at the same result using 3D seismic data and well logs, which has rarely been done in subsurface investigations (Parrish and Peterson, 1988; Chan and Archer, 2000; Loope and Rowe, 2003).

Figure 1b shows a satellite picture of Rub' al Khali, Arabia, taken by ASTER (2005). This is a modern analog to the dunes in our study area. First, the image clearly shows the spread of transverse dunes similar to this study. The wind direction (shown by the blue arrow) is east to west and is evident by the gradual dip (stoss side) on the right and steep dip (lee side) on the left of each sand dune. Second, the scale of the sand dunes

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Manuscript received by the Editor 30 October 2019; revised manuscript received 31 March 2020; published ahead of production 11 June 2020; published online 23 July 2020. This paper appears in *Interpretation*, Vol. 8, No. 4 (November 2020); p. SR23–SR26, 4 FIGS.
http://dx.doi.org/10.1190/INT-2019-0231.1.

also is similar where they are as high as hundreds feet and as distant as 2 miles apart.

Appearance on seismic data

Seismic sections reveal discontinuous reflectors in a certain interval, whereas continuous reflectors occur above and below it (Figure 2). A seismic to well tie shows that this interval reflects the Nugget Sandstone (Figure 3). The absence of any significant faults below or above the Nugget Sandstone interval indicates that the discontinuous reflectors are not inferring structural features but rather are formed by depositional processes. Horizon slices covering the Nugget Sandstone interval reveal parallel lineations that are most pro-

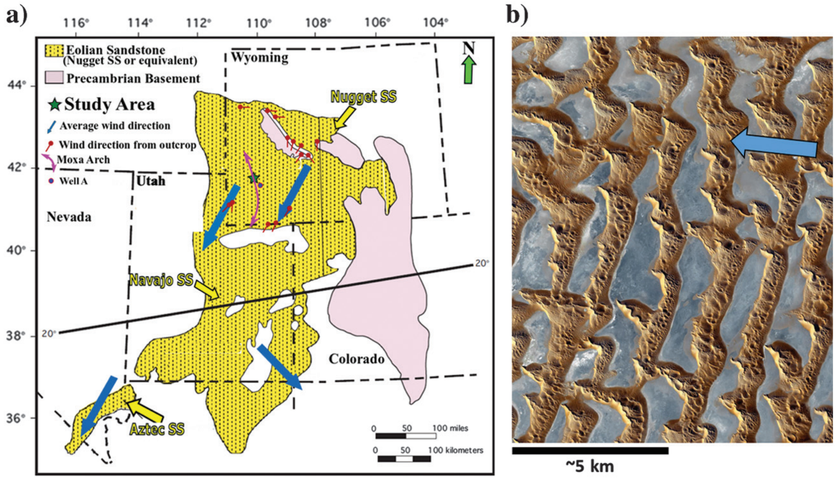

Figure 1. (a) The distribution of the Nugget Sandstone (and its equivalent, the Navajo and Aztec Sandstones). The big blue arrow shows the average paleo-wind direction. The red dipoles show the wind direction observed from the outcrop study (after Parrish and Peterson, 1988; Chan and Archer, 2000; Verma et al., 2018). (b) ASTER satellite image (after ASTER, 2005) of Rub' al Khali, Arabia. The flaxen yellow-colored linear feature represents the dunal sands, and the light-blue/white colors represent the interdunal evaporites/shales.

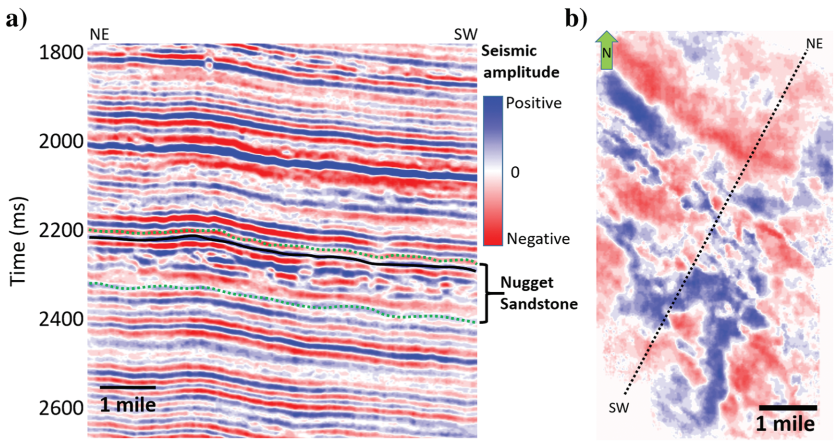

Figure 2. (a) Northeast–southwest-oriented vertical section through the seismic amplitude volume showing discontinuous reflectors in the Nugget Sandstone interval, outlined between the two green dotted lines. The solid black line represents a geophysical horizon just below the Nugget Sandstone top. (b) Time slice at 2285 ms (seismic amplitude volume) showing the lateral variation in seismic amplitudes. The vertical section in Figure 2a is along the dotted black line in Figure 2b.

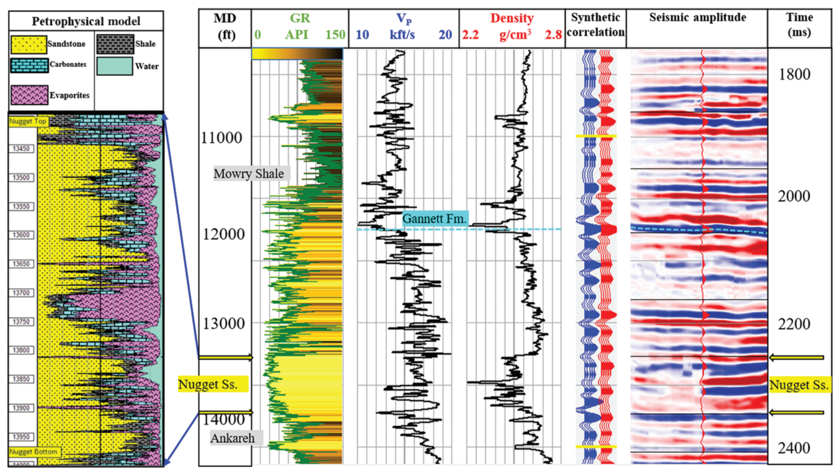

Figure 3. Petrophysical lithology model and seismic to well tie on Well A (the well location given in Figure 1). The leftmost track of the figure is a magnified section of the Nugget Sandstone interval, displaying the petrophysical lithology model; we first obtained the multimineral solution (results include quartz, illite, kaolinite, calcite, dolomite, anhydrite, halite, gypsum, and water) by stochastic inversion. To further simplify, we defined quartz = sandstone, kaolinite + illite = shale, calcite + dolomite = carbonates, halite + anhydrite + gypsum = evaporites. In the synthetic correlation track, the blue wiggles represent the synthetics, and the red wiggles are the seismic. The well synthetic to seismic correlation was approximately 70%.

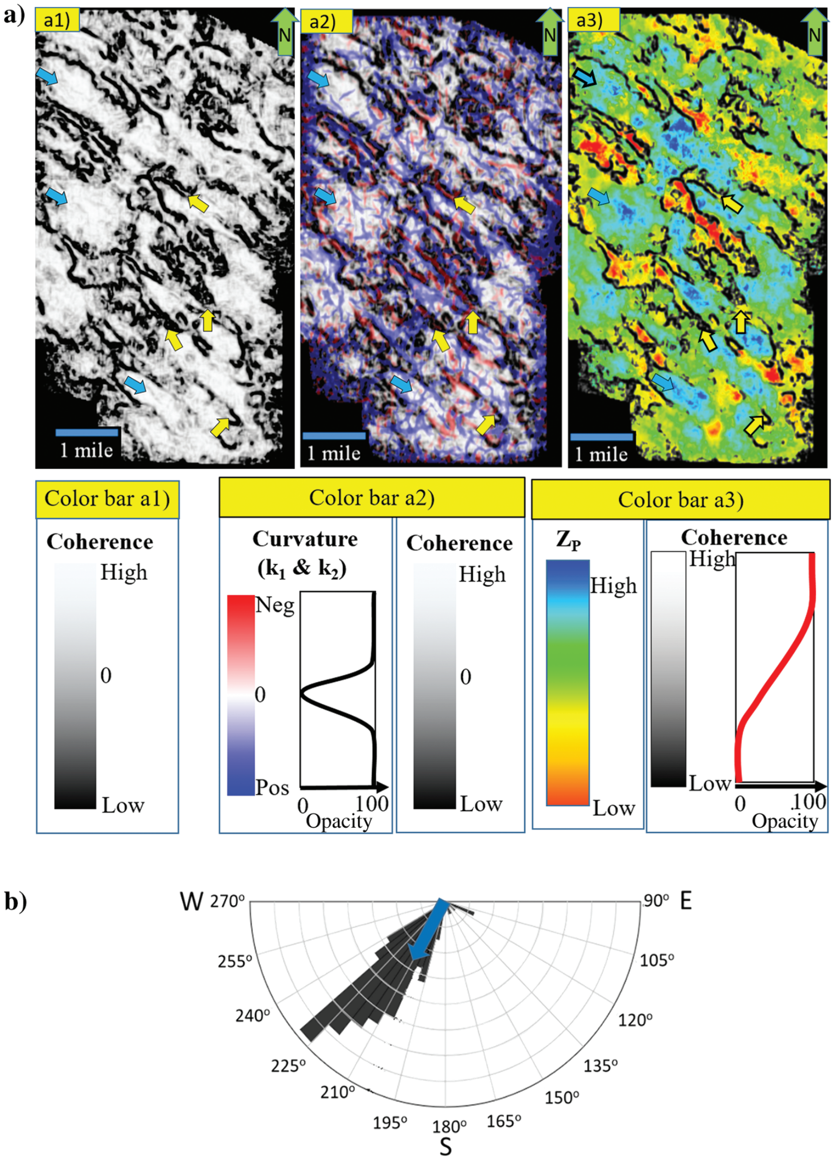

Figure 4. (a) From left to right: stratal slices of (a1) coherence attribute, (a2) most positive curvature (k_1) corendered with the most-negative curvature (k_2) and coherence, and (a3) acoustic impedance (Z_P) corendered with coherence. All stratal slices are taken 44 ms below the Nugget Sandstone top surface (Figure 2a). The blue arrows indicate the interdunes, whereas the yellow arrows indicate well-developed sand dunes. (b) The paleo-wind direction on the rose diagram (modified from Verma et al., 2018), computed from an average azimuth of various expected winds, is perpendicular to the lineaments. The blue arrow indicates the dominant wind direction obtained from outcrop studies in the nearby exposures of the Nugget Sandstone by previous authors (after Parrish and Peterson, 1988; Chan and Archer, 2000).

nounced within the central portion of the formation and up or down the stratigraphy. Coherence marks the boundaries between dunes and interdunes. Curvature infers the extent of the synforms (interdunes) and antiforms (dunes). Corendering these geometric attributes clearly shows that the boundaries are filled with the most positive curvature (antiform) and surrounded on both sides by the most negative curvature (synform).

Additional corendering of coherence and acoustic impedance on stratal slices reveals a relation between low-coherence anomalies and low-impedance anomalies (Figure 4a). We interpret the low impedance as high-porosity dunal sandstones and the high impedance as the interdunal areas composed of evaporites. A quantitative estimate of the prominent paleo-wind direction in the study area is found by computing the average azimuth of the lineations from the curvature attribute as approximately N 225° E.

Seismic interpreters who are not familiar with the background geology might interpret the features observed in Figures 2 and 4 as canyons on the continental slope, slope failure, marine bars, or contourites. We discarded these interpretations after our seismic-to-well tie that indicated that the interval of interest (Figures 2 and 4) is the Nugget Sandstone, which is an age-equivalent of the Navajo Sandstone deposited in the eolian environment. Second, we know from the literature that the Nugget Sandstone is an eolian sandstone (Figure 1a). The paleogeographic information shows no indication of marine incursion during the Early Jurassic time in the study area. In addition, the petrophysical inversion model shows the presence of evaporites (Figure 3), which is possible in the arid eolian environment (Blakey and Wayne, 2017).

Acknowledgments

The seismic survey used in this study was acquired and provided to us by the University of Wyoming with the research grant provided by the United States Department of Energy: Contract No: DE-FE0023328. We would like to thank CGG GeoSoftware for Hampson Russell, Schlumberger for Petrel, and IHS Markit for Petra software licenses provided to UT Permian Basin for research and education. Attribute Assisted Seismic Processing & Interpretation (AASPI) software was used to compute seismic attributes.

Data and materials availability

Data associated with this research are confidential and cannot be released.

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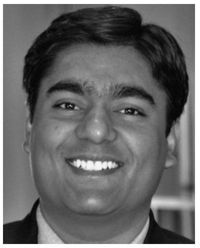

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