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Delineation of early Jurassic aged sand dunes and paleo-wind direction in southwestern Wyoming using seismic attributes, inversion, and petrophysical modeling

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ABSTRACT

Moxa Arch is a potential site for carbon sequestration in the state of Wyoming, recognized by the US Department of Energy. In this paper, we primarily focus on improving our understanding of the geology, including lithofacies and depositional environment, of Nugget Sandstone-a potential carbon storage reservoir, by integrating results from three different techniques including seismic attributes, seismic inversion, and petrophysical modeling. The Nugget Sandstone formation is primarily an eolian sandstone, deposited in the early Jurassic and is present throughout southwestern Wyoming. Seismic attribute analysis indicates the presence of NW-SE trending elongated geological features in the Nugget Sandstone interval. Based on our seismic and well log analyses, we interpret these features to be eolian sand dunes, which is consistent with the previous publications indicating a general NE-SW paleo-wind direction at the time of the deposition of Nugget Sandstone and other equivalent formations in Wyoming and Utah. The petrophysical analysis indicates that the Nugget Formation is mostly composed of quartz; however, clay and evaporites such as anhydrite and halite are also present. The acoustic impedance, derived from well logs, indicates that high porosity dunal sandstones correspond to low impedance values whereas interdunal evaporites are characterized by high impedance values. Combined analysis of seismic attribute coherence and inverted P-impedance discriminates the dunal and interdunal deposits in 3D seismic data volume; the low coherence defines the extent of low impedance dunal deposits. Detailed analysis of the curvature attribute from the seismic data indicates a dominant paleo-wind direction of approximately N225°.

1. Introduction

Our study area is located in southwestern Wyoming on top of the Moxa Arch, which is a gently dipping and doubly plunging anticline (~5°), extending from the south of the Uinta Mountains at the Utah/Wyoming border and go north up to the town of La Barge, Wyoming (Fig. 1). Moxa Arch and Rock Springs Uplift (RSU) were identified as two potential sites for carbon sequestration by the US Department of Energy (DOE). There has been significant research done on the RSU as a carbon sequestration site, whereas the Moxa Arch is less studied (Grana et al., 2017; Sharma et al., 2018; Surdam, 2013; Mallick and Adhikari, 2015; and Verma et al., 2016 among others). The Moxa Arch has several potential storage reservoirs including the Jurassic Nugget Sandstone, the Mississippian Madison Limestone, and the Ordovician Bighorn Dolomite. In the study area, an oil and gas company has been injecting CO_2 and H_2S in the Madison Limestone on the Moxa Arch, at the Shute Creek processing facility for over 10 years. The Nugget Sandstone is a heterogeneous and anisotropic eolian deposit, and is a producing formation in some parts of the Moxa Arch, which can be a challenge for its consideration as its potential for carbon storage. At the same time, Nugget Sandstone is a relatively shallow formation as compared with other potential storage formations (such as the Madison Limestone formation) in the area. Therefore, if proven as good storage reservoir, it would be a cheaper alternative for carbon storage than the other formations. Our survey location is critical, since the Naughton Power Plant, a coal-fired power station which emits up to 6 Mt of CO_2 per year, lies approximately 20 miles south-west of our study area (Campbell-Stone et al., 2011). This paper is focused on developing the geological understanding of the Nugget Sandstone and its potential for carbon storage.

Nugget sandstone in southwestern Wyoming is a lower Jurassic eolian sand deposit, and is equivalent to the Navajo Sandstone of

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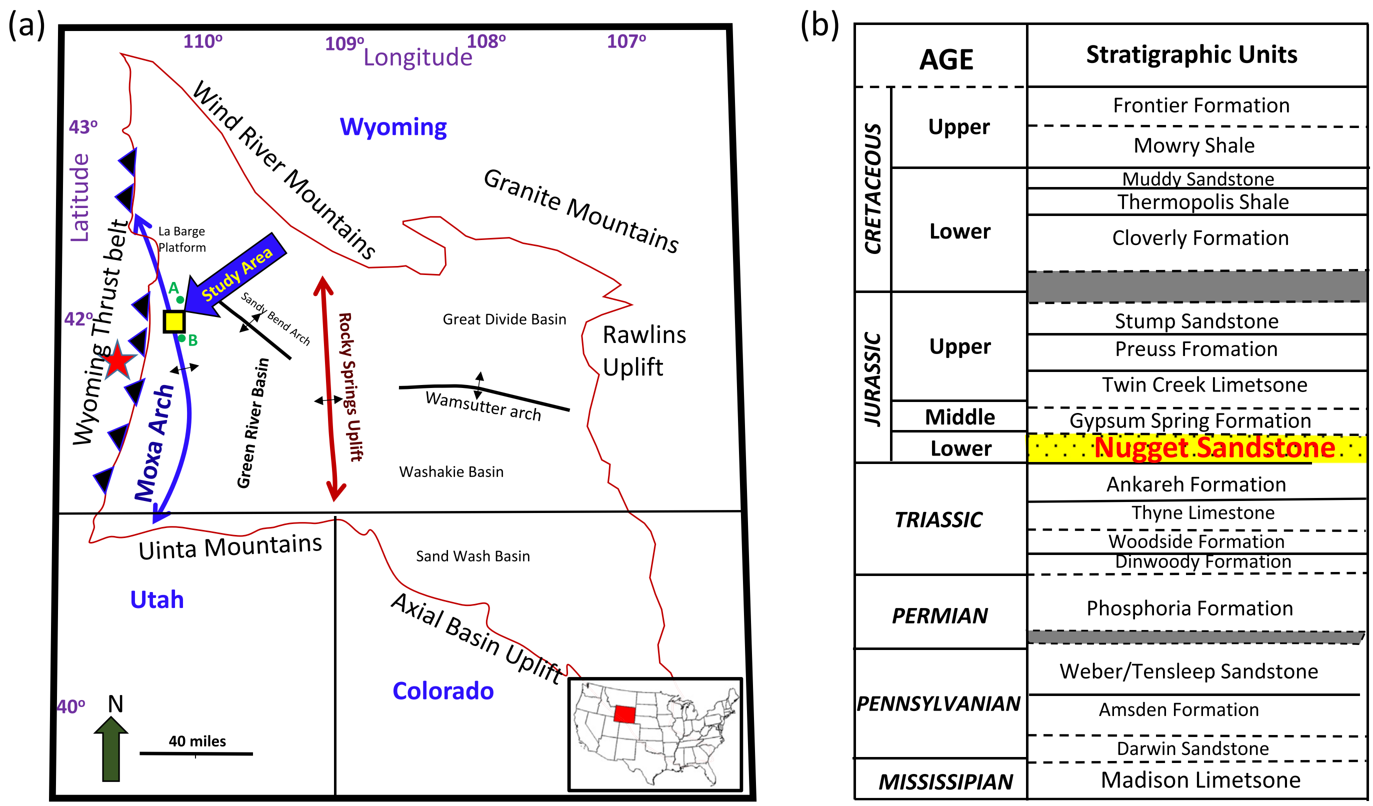

Fig. 1. (a) Location map of the Moxa Arch and Rock Springs Uplift in SW Wyoming (modified after Verma et al., 2016). The green dots next to the survey represent the approximate well location. A = Keller 1-12, and B = AGI 2-18 are the wells used for the study. The red colored star represent the location of the Naughton Power Plant. (b) Generalized stratigraphy of the Moxa Arch (modified after Thyne et al., 2010). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

southwestern Utah. Loope and Rowe (2003) compared Arizona, Utah, and Wyoming during the early Jurassic period with the present day Sahara Desert. Nugget Sandstone was deposited in a subtropical dune field in the present day northern Utah and southern Wyoming (Fig. 2a). Navajo sandstone, which is outcrops in several locations in Utah, has been heavily studied (Parrish and Peterson, 1988; Chan and Archer, 2000). Parrish and Peterson (1988) identified the wind direction for Nugget, Navajo and Aztec Sandstones (Fig. 2b) by analyzing their outcrops.

Seismic attributes can help us understand varying subsurface geological and stratigraphic features. Out of various attributes available in seismic literature, coherence and curvature attributes has been used in past to delineate different stratigraphic and structural features such as different types of channels, faults, folds and karst (Chopra and Marfurt, 2007; Qi et al., 2014, 2017; Khoudaiberdiev et al., 2017) However, paleo sand dunes were not particularly studied using these attributes. In our study, we analyze the seismic attributes, primarily curvature and coherence, to identify the shape of the paleo-sand dunes and attempt to identify wind direction during the time of the paleo-wind deposition. We also analyze well logs to understand the petrophysical properties of dunal and interdunal deposits. Further, we perform a post-stack seismic inversion, followed by an integrated analysis of seismic attributes, well logs, and seismic inversion results to identify dunal and interdunal deposits.

2. Geology of the study area

2.1. Moxa Arch

The Moxa Arch is an anticline stretching from the southern portion of the La Barge Platform to just north of the Uinta Mountains. In the northern part of the arch, and within our study area, the axis of the arch trends northwest to southeast but then changes to a northeast to southwest trend in the southern portion of the arch close to the Uinta Mountains. Because of its size and structural closure, the Moxa Arch has been the target of extensive hydrocarbon exploration since the 1960s with major gas and oil reservoirs being discovered all along the arch. Structurally, the Moxa Arch is a basement involved anticlinal structure with gently dipping arms that were created as the Wyoming thrust belt developed during the Laramide orogeny (Verma et al., 2016; Campbell-Stone et al., 2011). Moxa Arch contains approximately 22,000 ft (6.7 km) sedimentary strata above Precambrian basement. Mississippian Madison Limestone and Jurassic Nugget Sandstone are potential formations for carbon storage (Surdam, 2013). In our study area, the Nugget Sandstone lies at approximately 12,500 ft (3.8 km), and the Madison Limestone at 16,500 ft (5 km) below the surface. For the rest of the paper, we will focus on Nugget Sandstone formation.

2.2. Nugget Sandstone

The Nugget Sandstone is an eolian sandstone, deposited in the early Jurassic and is present across southwestern Wyoming both in the subsurface and as outcrop (Figs. 1b and 2). During the early Jurassic period, the western United States including Arizona, Utah and Wyoming, lied around 15°-25° latitude with the paleo-environment comparable to the present day Sahara Desert (Loope and Rowe, 2003). Based on the consistency of the prevailing wind direction, prevailing wind speed, and sand supply, different types of sand dunes can form. Fig. 2b shows the extent of early Jurassic Nugget Sandstone and Navajo Sandstone deposition. Predominantly eolian processes build these formations; they feature cross-bedded, low-angle to horizontally bedded and rippled, very-fine to coarse-grained sand in dunes, interdune areas, and associated environments (Lindquist, 1983).

Sand dune cross beddings can help in the identification of paleo-