



Thin-bedded reservoir analogs in an ancient delta using terrestrial laser scanner and high-resolution ground-based hyperspectral cameras



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ABSTRACT

Ground-based terrestrial laser scanning and hyperspectral sensors were used to image fine-scale heterogeneity in outcrops of prodeltaic heterolithic facies of Parasequence 6 of the Cretaceous Ferron Notom delta in Southern Utah. Previous work shows that Parasequence 6 is an upward coarsening fluvial-dominated, wave-influenced deltaic deposit containing heterolithic thin-bedded facies representing distal delta front and proximal prodelta environments. Primarily, the thin beds have been interpreted as turbidites, storm beds (tempestites), and hyperpynites. These deposits represent analogs for thin-bedded unconventional pay zones that lie at the margins of conventional deltaic sandstone reservoirs.

The terrestrial laser scanner was used to create a centimeter- to decimeter-scale, digital representation of the outcrops in three dimensions. Hyperspectral sensors record electromagnetic radiation reflected off the outcrops in 840 contiguous bands, which were then used to generate a spectral signature for each pixel sampled. The spectral signatures are a function of mineralogy, chemistry, surface alteration, grain-size, and cements, and were used to distinguish thin mudstones from sandstones within an interbedded succession at the base of a deltaic parasequence. Comparison between the spectral signatures recorded from the outcrop and those of reference materials, and with previous facies architecture studies, enables lithofacies to be identified and subsequently accurately mapped. Hyperspectral data are then draped over the terrestrial laser scanner model to generate a spatially-accurate detailed three-dimensional (3D) geologic map of the heterogeneity.

Approximately 100 m of outcrop was imaged laterally with the hyperspectral camera and terrestrial laser scanner on the previously mapped distal delta front and prodeltaic facies of Parasequence 6. Bed thickness data, based on measurements made along depositional dip versus strike, show that bed geometries are anisotropic. Reconstruction of the plan-view geometry shows that the thin-beds are lobate to elongate in plan-view profile and extend over distances of about 1 km, indicative of the dispersive waning sediment transport processes found in storm-influenced fluvial-dominated deltas. The lobate geometry suggests that beds are laterally discontinuous, with a width to thickness ratio on the order of <10,000 (i.e. a 10 cm bed extends for <1 km). The combined terrestrial laser scanner and hyperspectral data provide continuous 3D maps of grain-size and lithology. The maps which emphasize the continuity and dimensions of thin beds are among important factors which impact reservoir behavior.

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1. Introduction

Many hydrocarbon reservoirs contain thin-bedded facies with recoverable oil and gas. The thin-bedded facies are often at a scale which is not resolvable using typical logging methods. The difficulty in resolving thin-beds has created a need for other methods to characterize thin-bedded reservoir facies. Recent advances in ground-based remote sensing technologies, hyperspectral imaging and the use of Terrestrial Laser Scanners (TLS), have the potential to aid the study of

thin-beds in outcrops as reservoir analogs on macroscopic- and mesoscopic-scales in virtual 3D.

Thin-beds are found in nearly all siliciclastic depositional environments and are common features of prodelta and delta front sub-systems of deltaic depositional systems (Passey et al., 2006a). In the petrophysical literature, thin beds have been described as beds between 2.5 cm and 60 cm thick, with 60 cm being the maximum thickness, and near the maximum resolution of porosity logs and the highest-resolution resistivity logs (Passey et al., 2006b). In this study, thin beds refer to beds from 2.5 cm to 30 cm in thickness. Thin-bedded distal delta front and prodelta facies may contain significant reservoir heterogeneity (Bhattacharya, 2006). The plan-view profile of deltaic systems can offer clues as to the internal configuration of the various facies. In

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general, fluvial-dominated deltas are typically elongate to lobate shaped (Galloway, 1975), wave dominated deltas are cusate shaped, and tidal dominated systems are indented (i.e., embayed) and have been referred to as “estuarine” shaped (Galloway, 1975). Howell et al. (2008) established a methodology to quantify the relative proportion of wave-influence versus fluvial-influence based on curvature measurements taken on modern shorelines using satellite imagery.

This study used TLS and ground-based hyperspectral cameras and high-resolution photographs to gather geological data on sub-vertical cliff faces, with an emphasis on analysis of the lateral continuity of beds identified in the previous one-dimensional (1D) measured section.

Lateral mapping of thin beds is not commonly done, owing to the historical lack of popular interest in muddy facies, difficulties with parallax, and the propensity for muddy facies to form highly-weathered or covered slopes, making such analysis impractical. In addition, the use of integrated ground-based hyperspectral and TLS data at outcrop-scale for geological studies is still in its infancy. Other studies have investigated the use of these tools and have developed various data collection and processing methodologies (Kurz et al., 2012, 2013; Murphy et al., 2012; Buckley et al., 2013; Minisini et al., 2014; Hartzell et al., 2014; Okay and Khan, 2016). The instruments, data processing, and limitations are discussed in the following sections.

This study had two goals of equal importance. One goal was to explore and document the capabilities, workflows, limitations, and application methodologies of integrated TLS and ground-based hyperspectral technologies as applied to siliciclastic sedimentology. The second goal was to use the aforementioned tools to study lateral variation of delta-front to prodelta thin-beds, with emphasis on estimating plan-view geometry based on cross-sectional measurements on multiple cliff faces and investigate if the estimated plan-view geometry could be tied to other factors, such as bedding thickness, net-to-gross, dominant depositional processes, and grain-size.

2. Study area and geological background

The focus of this study is the Ferron Sandstone Member of the Mancos Shale (Fig. 1) in Southern Utah's Notom Delta complex near Capital Reef National Park. The Notom Delta has been shown to contain forty-three parasequences, eighteen parasequence sets, six sequences and is ca. 90.6–90.7 Ma (Turonian) in age (Zhu et al., 2012). This study expands on the previous works by Li et al. (2015) and Seepersad (2012) in Parasequence 6 on a micro- to mesoscopic scale. Parasequence 6 crops out along Highway 24 between the Coal Mine road exit and Hanksville on Highway 24 (Fig. 1).

Parasequence 6 (Zhu et al., 2012) has been interpreted regionally to record a descending regressive shoreline trajectory, exhibiting a degradational to progradational stacking pattern, characterized by cross-bedded distributary channels scouring into underlying delta front heterolithic facies (Zhu et al., 2012), the latter of which are the focus of this study. Based on meter-scale mapping and facies associations, different areas of Parasequence 6 have been interpreted to be either fluvial-dominated or wave-dominated depending on where the data were collected; the mixed interpretations in large-scale mapping are attributed to asymmetry in the delta (Bhattacharya and Giosan, 2003; Li et al., 2011, 2015). Although this study was conducted in the river-dominated portion of the delta, evidence of storm-wave influence was also observed in a number of sandstone beds. The detailed sedimentology of Parasequence 6 has been fully documented elsewhere (Li et al., 2011, 2015; Zhu et al., 2012; Seepersad, 2012; Ahmed et al., 2014) and only the most salient details are highlighted below.

The finest scale studies of Parasequence 6 were completed by Seepersad (2012) and Li et al. (2015) (Fig. 2). Using traditional geologic methods, detailed measured sections at centimeter-scale resolution were used to describe each thin bed according to its grain size, physical and biogenic structures (details are in Li et al., 2015). The overall upward increase in sandstone bed thickness and proportion indicated

deltaic progradation. A general lack of bioturbation was interpreted to indicate high sedimentation rates, consistent with deposition in a river-dominated delta (MacEachern et al., 2005; Li et al., 2011, 2015).

Ten distinct facies were recognized, which were used to aid in the interpretation and differentiation of turbidites, tempestites and hyperpycnites. Key facies which allowed for these interpretations include hummocky cross-stratification, massive bedding, planar bedding, wave ripple cross-lamination, starved ripples, asymmetrical cross-bedding (current ripples), normally graded and inversely graded beds.

Wave rippled or hummocky cross-stratified sandstone beds were interpreted to represent storm events (tempestites), whereas massive, parallel to current ripple-laminated, normal or inverse graded beds were interpreted as turbidites and hyperpycnites, respectively. The latter are inferred to be directly river-fed. Seepersad (2012) and Li et al. (2015) showed that the heterolithic facies in Parasequence 6 in this study area reflect about 65% to 70% river-dominated processes and about 30% to 35% storm wave-reworking, indicating a fluvial-dominated, storm-wave-influenced setting. In general, we interpret storms to have driven the Ferron rivers into a flood-state such that most of the storm beds are likely also fed by the associated Ferron River. No evidence of tidal processes was observed.

3. Methods

3.1. Instruments

This study utilized a Riegl VZ-400 3D TLS system. The VZ-400 has a 1550 nm laser and a manufacturer-reported range repeatability of 3 mm. The system is also equipped with a Nikon 3200 digital SLR camera with a 50 mm lens that mounts directly on top of the scanner and allows for the point cloud to be easily colorized in true color, or as a function of amplitude or reflectance. All scan data were aligned with a root mean square error of 3 mm (0.12 in.). The resultant point cloud contained an average of 10+ points per square centimeter.

Ground-based field deployable hyperspectral system with two separate SPECIM sensors collectively sample data between 400 and 2500 nm, representing the visible near-infrared (VNIR) and short-wave infrared (SWIR) ranges of the electromagnetic spectrum. The data were collected at distances of 30 to 50 m from the outcrops. Resolution in that range is 0.9–1.4 cm² in VNIR and 1.5–2.5 cm² in SWIR. A summary of specifications for the hyperspectral cameras is given in Table 1.

Approximately 2000 photographs of the study areas were taken with a Nikon 3200 digital SLR camera with a Sigma 500 mm lens mounted upon a Gigapan, a robotic camera mount for automating large-scale panoramas. The photographs were at a resolution high enough to discern small-scale sedimentary structures (pixel density was typically above 10 million pixels per square meter). They were used to aid in the identification of bedding planes that were often hard to discern based on TLS data alone. The difficulty of tracking bedding planes in the TLS data was not due to a lack of resolution, but rather a lack in discernible weathering relief in many portions of the outcrops. This includes beds covered by mud, gypsum, light vegetation and fallen blocks from above.

3.2. Data processing

Multiple TLS data sets were integrated to provide a 3D spatial framework onto which thin-beds could be mapped. The beds were identified and mapped laterally in multiple geographic directions. Bed thickness was measured at horizontal spacing intervals of 20 cm. The thickness variation data was ultimately used for extrapolation away from the measured data. The first phase of mapping was completed using only the TLS point cloud and relied on weathering relief to distinguish individual beds, similar to the approach employed by Olariu et al. (2010). In order to correctly interpret the bedding planes, the second stage of

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