PSQuantitative Outcrop Characterization of Incised Valley Fill Combining UAV-Based Photogrammetry and Traditional Geologic Field Methods, Kaiparowits Plateau, Southern Utah, USA*

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Abstract

A scalable, readily repeatable methodology for quantitative outcrop characterization has been developed combining Unmanned Aerial Vehicle (UAV) based photogrammetry with more typical field-based outcrop characterization techniques. The utility of this methodology is demonstrated in extracting high-resolution dimensional data from estuarine incised valley fill deposits exposed in the Cretaceous John Henry Member of the Straight Cliffs Formation in southern Utah, USA. While the use of photogrammetry to produce 3D outcrop models is not new to the geosciences, the increased availability of UAVs has improved our ability to efficiently collect high-resolution outcrop imagery necessary to develop these models. Spatially oriented outcrop models facilitate quantitative outcrop characterization from the bedding- to petroleum systemscale. Transgressive estuarine incised valley fills possess significant potential as hydrocarbon reservoirs in the subsurface, though the dynamic nature of tidal systems make them especially heterogeneous. The complex architectures expressed from the geobody- to reservoir-scale introduce substantial uncertainty to reservoir volume and performance prediction. Quantitative outcrop analog characterization provides dimensional data for geobodies and key surfaces required to improve subsurface reservoir predictions. A 3D outcrop model was produced using Structure from Motion (SfM) to combine overlapping aerial imagery and GPS data collected in the field. Decimeter-scale stratigraphic sections were then draped over the outcrop model, serving as the primary control points for an iterative process of 3D geologic interpretation (definition of geobodies and identification of key bounding surfaces). Dimensional data was extracted to quantify the thickness, aerial extent, stacking, and internal architecture of a laterally accreting mid-estuarine bar and multiple tidal channels. The thickness and lateral extent of key bounding surfaces were also measured. This data has been added to a dimensional database for paralic systems created as part of an ongoing research effort and will be used to inform future performance prediction simulations. Based on the internal architecture and stacking of geobodies within the incised valley fill we expect significant connectivity between channels and bars, where they overlap, and with the underlying sand-rich shoreface deposits. Internal shale drapes form the greatest potential for reservoir compartmentalization.

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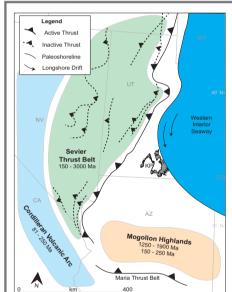
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Objectives

- 1) Develop a 3D outcrop model of a preserved mid-estuarine bar combining Unamanned Aerial Vehicle (UAV) -based photogrammetry and traditional field-based outcrop characterization techniques.
- 2) Identify and describe the nature/extent of bounding surfaces which could influence the static and dynamic conenctivity of a mid-estuarine bar and surrounding reservoir units.
- 3) Create a quantitative dataset which describes the facies architecture, transitions, and internal stacking from bed- to geobody-scale.

Geologic Background



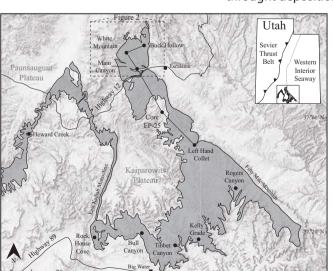
Late Cretaceous Tectonics and Sedimentation

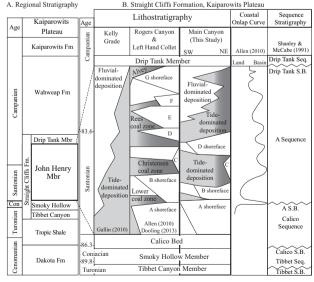
Turonian to early Campanian Straight Cliffs Formation was deposited in the retroarc foreland basin which developed in response to crustal loading of the Sevier Thrust Belt

In the Kaiparowits Plateau, the Straight Cliffs Formation records deposition of siliciclastic detritus derived from the Sevier fold and thrust belt, Mogollon Highlands, and Cordilleran Volcanic Arc carried by a northeast flowing distributary fluvial system (Lawton et al., 2003; Szwarc et al., 2014)

Complex interactions of this fluvial system with transgressive-regressive cyclicity of the Western Interior Seaway are captured in outcrops uplifted during the Cretaceous Laramide Orogeny

Left: Regional tectonic setting during the Late Cretaceous time. Szwarc et al (2014) used detrital zircon ages, sandstone composition data, and paleocurrent analysis to identify a pervasive SW to NE flowing axial fluvial system present throught deposition of the Straight Cliffs Formation.

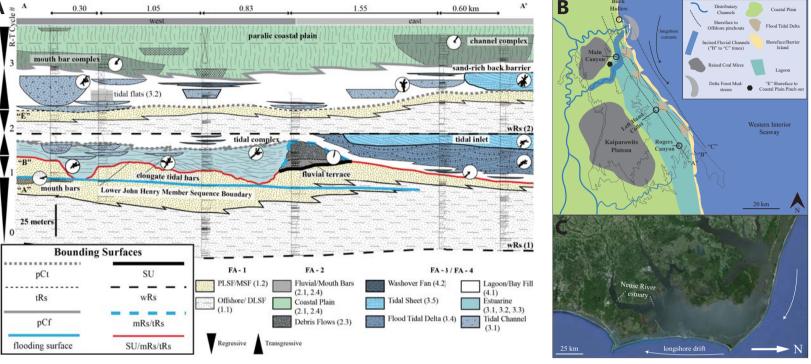




Above Left: Map of the Kaiparowits Plateau with exposure of the Straight Cliffs Formation in dark grey, highlighting locations of past research by the Rocks2Models industry consortium. Fluvial strata transition to the NE-E across the Plateau into paralic coal bearing strata with zones of tidal influence documented in Tibbet Canyon and Kelly Grade. The eastern Plateau preserves shoreface and paralic strata with incised esturine valleys and fill exposed near Main Canyon in the north.

Above Right: The John Henry Member of the Straight Cliffs Formation consists of siliciclastic sandstone, mudstone, and coal divided into 7 shoreface successions (A-G) identified by Peterson (1969). These shoreface successions provide inportant stratigraphic context for interpretation of the complex depostis of the eastern Plateau. Evidence of transgressive estuarine fill of fluvially incised valleys above the A shoreface are most pronounced along Highway 12 and in Main Cayon, the primary study area for this research.

Main Canyon Study Area: Stratigraphic Context



A) Correlation of strata in the Main Canyon study area. The lower to middle John Henry Member records the west-to-east progradation of shoreface parasequences and the development of a shore-parallel incised-valley backfilled with a complex assemblage of high-energy tide-dominated estuarine deposits. Fluvial terrace deposits and debris flow record incision and collapse of the valley wall, respectively. During the late stages of valley infilling, a landward-migrating back-barrier platform overrode the valley, forming flood-tidal delta and inlet deposits that thin onto the valley flank. B) Paleogeographic sketch of the Kaiparowits Plateau during deposition of transgressive estuarine fill in Main Canyon. Facies belts throughout the plateau tend to trend northwest to southeast and parallel the shoreline. Raised coal mires in the center of the Plateau deflected fluvial systems to the north. C) Satelite image of incised-valleys at Pamlico Sound, North Carolina. The shore-parallel orientation of the Neuse River estuary makes it a potential modern analogue for the incised-valley and estuarine fill observed in Main Canyon. Images and text adapted from Chentnik et al., 2015.

Utility of Unmanned Aerial Vehicles (UAVs) for Outcrop-Based Research



UAV-based photogrammetric models enhance outcrop characterization and interpretation by providing:

- Increased ability to visualize otherwise inaccessible portions of the exposure
- 2) Added perspective at different scales of observation facilitated by the ability to rapidly zoom in and out
- 3) Myriad vantage points and false coloration to highlight geologic features
- 4) A framework for geospatial analysis and the quantitative interpretation of structural geometries and sedimentological architectures
- A geological/geostatistical framework for development of dynamic flow models used to elucidate flow behavior

Text adapted from Jones et al. (2008). Calibration and validation of reservoir models: the importance of high resolution, quantitative outcrop analogues. Geological Society of London, Special Publications.

Recognition of a Mid-Estuarine Bar in Outcrop



Drone-based image from Main Canyon of estuarine fill. Red line marks an undulatory erosional unconformity between shoreface sandstone below and estuarine bar fill above. Sandstone beds dip landward in direction of deposition with the outcrop top marked in yellow.



The outcrop consists of multiple stacked 0.5-6.0 m thick sandstone beds



Sandstone beds are separated by laterally extensive shale drapes. The deposits often contain tidal rythmites and double mud drapes



Mud rip-ups ranging from 1-30 cm in length are commonly found at the base of sandstone beds



Fining-upward packages of coarse to very-fine sand are common within individual sandstone beds



Internal bedforms include laminar to wavy bedding and cross-beds. Cross-bed foreset angles tend to increase upward



reversals in paleoflow indicators (cross-beds shown above)



Near the center of the outcrop, estuarine sandstone beds are separated from the underlying shoreface deposits by laterally extensive interbedded sandstone and shale. Deformation of underlying sediments indicates rapid deposition



Toward its landward extent, sandstone beds are separated from underlying shoreface deposits by a conglomeratic tidal lag (absent interbedded sandstone and shale present elsewhere), suggesting the potential for localized dynamic connectivity



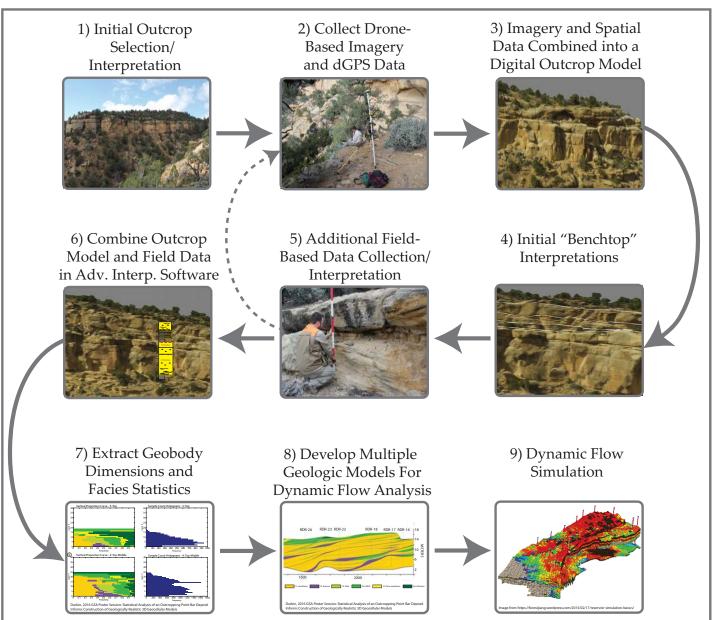
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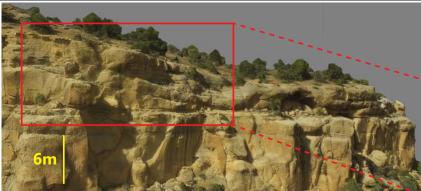
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Workflow



Above: Flow chart outlining the general workflow for quantitative outcrop characterization using both UAV-based photogrametry and traditional field-based methods. The outcrop selected for this study provides 3D exposure of a preserved midestuarine bar and surrounding deposits, making it particularly well suited for this type of 3D charaterization study. Differential GPS (dGPS) data were combined with aerial photography using structure-from-motion (SfM) software. This software provides the highest resolution version of the outcrop model, making it particularly useful for interpretation at multiple scales.

Outcrop Model Resolution



Right and Below: The 3D Outcrop Model produced using structure-from-motion software is of a high enough resolution that complex surfaces and facies heterogeneities can be resolved down to the bedding scale.



Key Features From The Outcrop

A) Lenticular sandstone bodies are observed between flatlying bar deposits toward the northern extent of the outcrop

B) Flute casts at the base of a sandstone bed indicate paleoflow to the southwest.

C) Deformed and eroded beds underlying sandstone beds indicate rapid deposition.

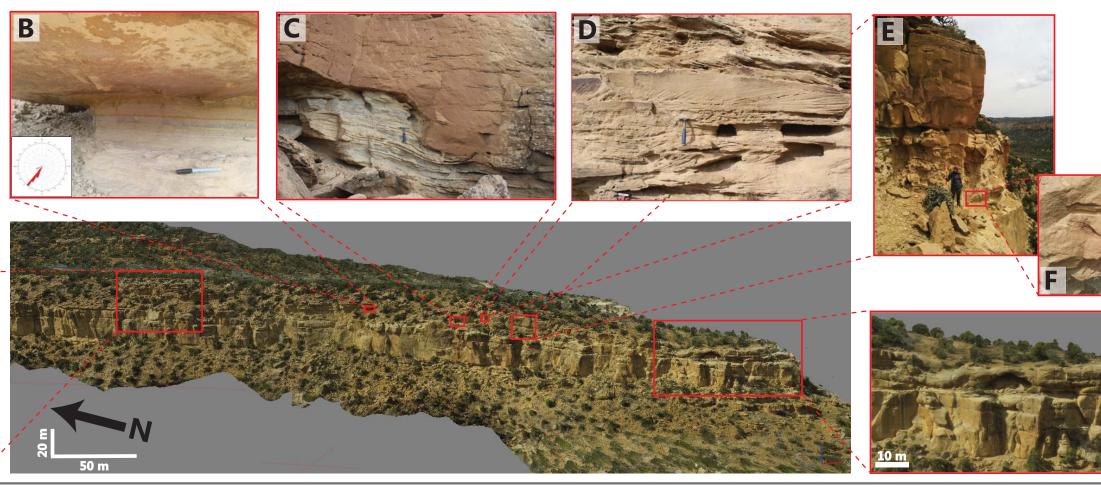
D) Bidirectional cross-bedding typical of tidal/estuarine env.

E) Near the middle of the outcrop, thick (up to 6 m) sandstone beds are separated from underlying shoreface deposits by a chaotic mixture of sandstone and shale.

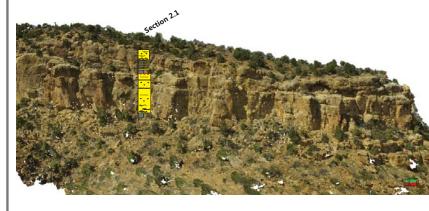
F) Bedded rip-up clasts up to 10 cm long are common in the chaotic beds noted above.

G) At the southern extent of the outcrop, estuarine sandstone beds and shoreface deposits are separated by a coarse lag.





Advanced Interpretation and Geologic Modeling



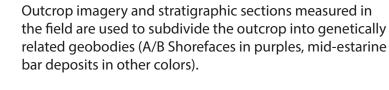
While some of the fine-scale resolution is lost in this step, Petrel provides a comprehensive platform for combining all available geologic data into a 3D rendering for viewing and interpretation.

The georeferenced digital outcrop model is brought into

Schlumberger's Petrel Platform as a point cloud using

PointCloudViz, a Petrel plugin by Mirage Technologies.

Visualization of the outcrop and associated geologic data enhances 3D interpretation and facilitates ongoing collaboration.



Quantitative analysis of geobody dimensions, stacking, and internal facies trends (transition probabilities) provide data essential for the construction of probabalistic static and dynamic simulations.

Conclusions/Next Steps

- 1) A 3D outcrop model of a preserved mid-estuarine bar has been created, combining UAV-based photogrammetry and field-based geologic characterization.
- 2) Key characteristics of a preserved mid-estuarine bar include: stacked sandstone beds (approx. 130 m long and 3.5 m thick) separated by laterally extensive mudstones and shales (0.1 to 0.5 m thick), net-landward deposition, rip-up clasts at the base of sandstone geobodies, bidirectional tidal indicators, steepening upward trough-cross stratification, and fining upward sandstone packages.
- 3) Though generally shale draped, tidal lags within the lower bounding surface suggest the potential for localized connectivity with underlying shoreface deposits.
- 4) Future efforts include ongoing field characterization, quantification of geobody dimensions/facies architecture, and development of a probabalistic static model.

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