TERRESTRIAL LASER SCANNING COMBINED WITH PHOTOGRAMMETRY FOR DIGITAL OUTCROP MODELLING

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ABSTRACT:

The integration of 3D modelling techniques is often advantageous for obtaining the most complete and useful object coverage for many application areas. In this paper, terrestrial laser scanning and digital photogrammetry were combined for the purposes of modelling a geological outcrop at Castle Creek, British Columbia, Canada. The outcrop, covering approximately 2.5 km^2, comprised a smooth, scoured surface where recent glacial retreat had left the underlying sedimentary rocks exposed. The outcrop was of geological interest as an analogue to existing hydrocarbon reservoirs, and detailed spatial data were required to be able to map stratigraphic surfaces in 3D over the extent of the exposure. Aerial photogrammetry was used to provide a 2.5D digital elevation model of the overall outcrop surface. However, because the sedimentary strata were vertically orientated, local vertical cliffs acted as cross-sections through the geology, and these were surveyed using a terrestrial laser scanner and calibrated digital camera. Digital elevation models (DEMs) created from both methods were registered and merged, with the fused model showing a higher fidelity to the true topographic surface than either input technique. The final model was texture mapped using both the aerial and terrestrial photographs, using a local triangle reassignment to ensure that the most suitable images were chosen for each facet. This photorealistic model formed the basis for digitising the geological surfaces in 3D and building up a full 3D geocellular volume using these surfaces as input constraints. Because of the high resolution and accuracy of the input datasets, and the efficacy of the merging method, it was possible to interpret and track subtle surface separations over the larger extents of the outcrop.

1. INTRODUCTION

The study of geological outcrops is an important area of research within the earth sciences, offering the opportunity to enhance the understanding of subsurface rock formations using those exposed on land (Pringle et al., 2004). Most relevant is the use of sedimentary outcrops that form analogues to existing hydrocarbon reservoirs which cannot be directly accessed by geologists, and which are often limited in terms of the spatial information available and the cost of obtaining new data. By studying an exposed outcrop, such as a cliff section or quarry, geologists can get insights into the processes that occurred at the time of deposition, and make quantitative measurements regarding the orientation and thickness of layers, the material composition, the presence of faults or fractures, and how these various factors change over distance. By applying such knowledge to subsurface reservoirs where similar depositional processes or structural geology occur can aid the modelling of extraction strategies.

Reservoir modelling is an important stage in the exploration of subsurface hydrocarbons. Available data, including rock core logs and seismic interpretation, are integrated into software packages that allow the creation of a 3D geocellular volume representing the reservoir. Layers and faults constrain the physical development of the volume, while the geological interpretation and rock compositions dictate the population of the grid with properties such as porosity and permeability.

Use of an exposed outcrop analogue increases the fine-scale understanding of the geological processes, offering the application of higher resolution measurements to add information to the reservoir model (Enge et al., 2007). Use of aerial and terrestrial spatial acquisition techniques, such as photogrammetry and laser scanning, offer the potential to dramatically increase the accuracy of measurements made, and open up new research possibilities, at various scales (Bellian et al., 2005; Buckley et al., 2008).

This paper documents the integration of two data collection methods, terrestrial laser scanning and photogrammetry, for building a high-resolution photorealistic model of an outcrop at Castle Creek, British Columbia, Canada. This model formed the input for reservoir modelling to aid understanding of geological processes exposed in the analogue.

2. STUDY AREA

The Castle Creek outcrop is situated in the Cariboo Mountains, British Columbia, Canada, a mountain range that forms part of the western margin of Canada and was formed primarily during the Mesozoic period (Ross et al., 1995). The Castle Creek outcrop is a 2 km thick succession of sandstone and mudstone belonging to the geological group known as the Windermere Supergroup. Although deposited in a near-horizontal setting, in a deep-marine environment, uplift

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during the mountain building process has resulted in the strata being rotated by approximately 95°, so that they are near-vertical. Consequently, a 2 km cross-section through the layers is now accessible for study. In addition, due to the recent retreat of the Castle Creek glacier, the surface of the outcrop has been polished and is almost free of vegetation (Figure 1). These factors make the outcrop attractive for study, and it is interpreted to be an analogue for hydrocarbon fields being explored in similar margins, such as offshore Brazil and the Gulf of Mexico (Schwarz and Arnott, 2007).

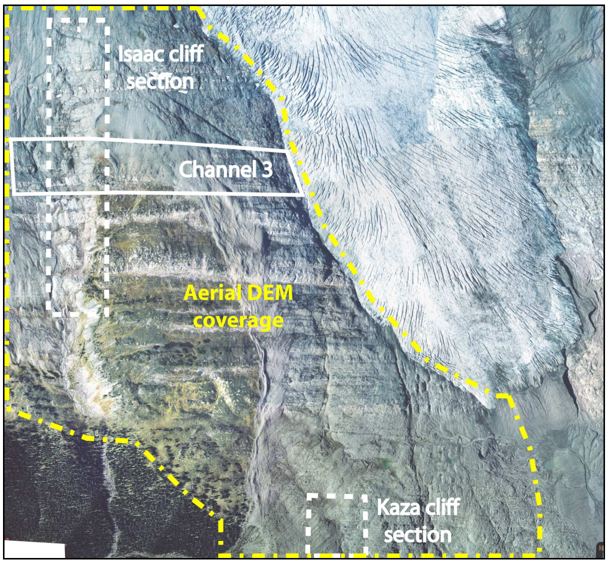

Figure 1. Photomosaic of the Castle Creek study area, showing extents of the aerial DEM coverage (dashed-dotted line) and the location of cliff sections scanned using the laser scanner (dotted lines). Size of area approx. 2.3 km × 2.3 km.

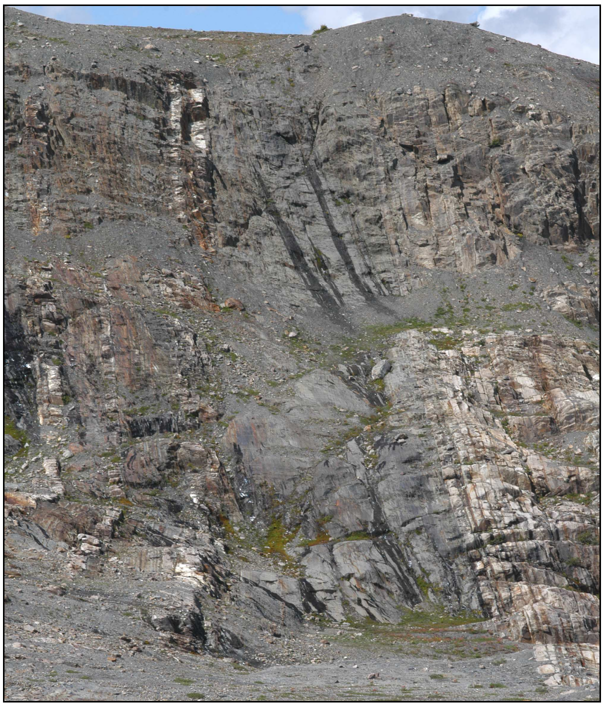

Figure 2. Detail of near-vertical cliff in the Isaac section (height c. 90 m).

Six major sandstone channel bodies have been interpreted within the outcrop, and one of these (called Isaac Channel 3 from the Isaac Formation at the top of the section) was used as a detailed case to test the full workflow from data capture to reservoir modelling (Section 6).

Although a degree of topographic undulation was present over the extents of the area, the outcrop surface provided essentially a 2D section through the geology. This meant that layers could be easily tracked across the exposed outcrop face, but to obtain the full 3D information needed for measuring layer orientations and separations, a certain amount of height difference was needed. The level of three-dimensionality found in an outcrop is important to measure the orientation (gradient and aspect) of layers, as with only a 2D cross-section these values cannot be found (e.g. Buckley et al., 2008). In the case of the Castle Creek area, near-vertical cliffs, up to 100 m high, were present across the outcrop (Figure 1), which provided exposure in the third dimension (Figure 2).

3. DATA ACQUISITION

Because the Castle Creek outcrop mainly had fairly smooth topography, a 2.5D aerial representation was most suitable to create a DEM. However, the requirement for high accuracy in the cliff sections, so that layer orientations could be determined over a relatively short distance, meant that a combination of aerial and ground-based data acquisition was chosen. Although airborne laser scanning would have been a feasible option to obtain the aerial terrain data, a major requirement for this project was also the ability to interpret the geology directly onto a virtual reality model, by digitising features. Therefore, high resolution imagery for texture mapping was essential. Additionally, stereo photographs had already been captured during an earlier phase of this project, and were available for photogrammetric processing.

Aerial photogrammetry provides a relatively routine and cost-effective means of capturing a 2.5D surface (especially when the imagery had already been acquired), and in this case was not hampered by the existence of low texture areas to interfere with automated image matching algorithms, nor tall vegetation to require much editing. Texture was available at high resolution for interpreting the geology.

For the near-vertical cliff sections, however, the aerial photogrammetric DEM alone would have provided a very poor representation of the ‘true’ topography. Deviations caused by heavy interpolation by only a limited number of 2.5D points would have been too high for the accurate modelling required. Therefore, terrestrial laser scanning was chosen to complement the aerial photogrammetry. This had the advantage of being an active technique, meaning that problems with image modelling of complex surfaces were avoided (Briese et al., 2003). The complementary nature of photogrammetry and laser scanning is widely discussed within the literature, especially with respect to the visualisation of modelled objects (e.g. El-Hakim et al., 1998; Axelsson, 1999; Briese et al., 2003).

The aerial photography dated from summer 2001, and was captured using a calibrated Zeiss RMK Top 30 camera with 300 mm lens. A flying height of around 3300 m was used. Combined with an average terrain height of 2000 m, this flying configuration gave an approximate photoscale of 1:4000. 70% overlap and 10% sidelap existed. A block of 12 photos, from three strips, covered the study area outlined in Figure 1; these photos were scanned at 13 µm resolution, resulting in a ground pixel spacing of c. 0.1 m.

The terrestrial laser scanning survey was carried out in August 2006, using a Riegl LMS-Z420i scanner (Riegl, 2009). This scanner had an effective maximum range of around 650 m (based on the reflectance of natural rock targets found in the Castle Creek outcrop), a quoted accuracy of 0.01 m, and a point acquisition rate of up to 12,000 points per second. The software RiSCAN Pro (Riegl, 2009) was used in the data collection and post-processing.

Two cliff sections were scanned, the Kaza and Isaac sections marked on Figure 1. The Isaac section (including the Isaac Channel 3 detailed study area) was 900 m long, 200 m deep, and up to 90 m high. The smaller Kaza section was around 450 m long, 170 m deep and 50 m high. Six scan positions were needed to cover the length of the Isaac cliff section, while the shorter Kaza section required just four. For both areas, at least 20% of overlap between adjacent scan positions was collected. The scans were collected at an average range of c. 350 m from the Isaac cliff and c. 100 m from the Kaza cliff. The point densities at these ranges were around 0.12 m (Isaac) and 0.08 m (Kaza).

Digital imagery of the cliff sections was also captured from the ground to provide additional high resolution texture for integration into the virtual reality model of the outcrop. A Nikon D100 camera was utilised, with 85 mm and 50 mm lenses mounted for the Isaac and Kaza sections respectively. The focal lengths of both lenses were fixed for the duration of the project, and calibrated both before and after the data collection campaign to ensure a stable calibration. The main advantage of the photography was the increase in resolution over the aerial data (especially in the vertical sections): the Nikon D100, with the 85 mm and 50 mm lenses and a pixel size of 7.8 µm, gave a ground pixel size of better than 0.04 m for the Isaac images and better than 0.02 m for the Kaza images. Imagery was captured so that, where possible, image rays were as close to normal as possible to the cliff face. This was to ensure the best results for the later texture mapping phase of processing (Debevec et al., 1996). The images were later registered to the laser scanner data using RiSCAN Pro, by manually measuring tie points on corresponding natural features between the image and laser data.

A GPS system was mounted to the laser scanner, and used to register the scan positions to the project coordinate system. Data were post-processed relative to a base station operating within the extents of the study area. Precise point positioning from three days of observation determined the base station coordinates, and baselines to the scanner centres were calculated with a few centimetres precision in UTM zone 10.

4. MODELLING AND REGISTRATION

A limited number of natural ground control points (GCP) had been collected previously using real-time kinematic GPS, though because of the difficulties with accessibility and the rugged terrain, the distribution was not ideal for carrying out an accurate aerial triangulation of the 12-photo block (Wolf and Dewitt, 2000). Instead, the GCPs were used to give an approximate orientation, and surface matching was employed to refine the orientation. Aerial triangulation with the GCPs resulted in a correct relative orientation, but with the absolute block position being affected by an offset corresponding to the poor ground point configuration (>1 m in the Isaac section that was farthest from the GCPs). A triangular irregular network DEM was extracted from the triangulated block for the area defined in Figure 1, with breaklines defined along sharp changes in slope. This DEM consisted of around 460,000 triangles (average point spacing c. 3 m).

The laser scan point clouds were registered with the iterative closest point (ICP) algorithm implemented in PolyWorks (InnovMetric, 2009), using overlap between the scans to recover the orientations relative to a single scan held fixed in the centre of each cliff section. Although this approach may not be as accurate as using conventional control points, benefits could be found in reducing the costs of expensive field time, an increase in redundancy, especially where almost no vegetation was present, and the ability to quantify the mismatch between overlapping surfaces (Buckley and Mitchell, 2004). The method is still applicable in areas with high vegetation cover, but registration results must be carefully checked as the vegetation points can show up as outliers and affect the solution. For both the Isaac and Kaza cliff point clouds registration results were good, with mean errors very close to 0.0 m, and standard deviations better than 0.1 m. Once the point clouds had been matched to a single coordinate system, they were transformed to the UTM system using the positions of the scanner centres (with RMS of 0.060 m). The transformed point clouds were merged and decimated by c. 60% to reduce the point density in overlapping areas, as well as to reduce the overall number of points. This made data handling more comfortable, without significantly reducing accuracy. Meshing of the point clouds was performed, resulting in 1.1 million triangles for the Isaac cliff section and 500,000 triangles for the Kaza section.

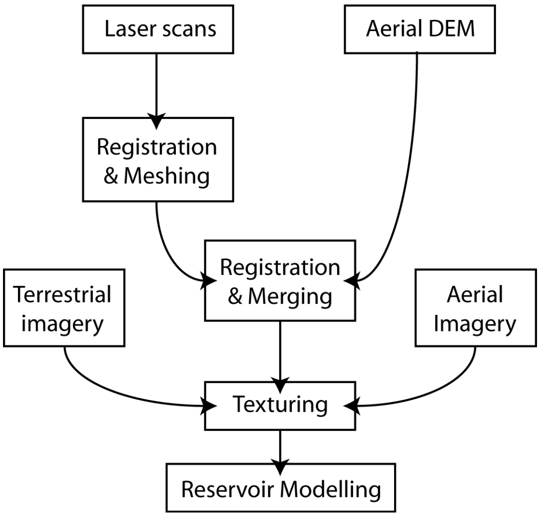

Figure 3. Workflow for data registration method.

Once triangle models had been created for the laser and aerial data, both datasets were in approximately the correct UTM position. However, the discrepancy introduced by the limited GCP coverage was present that meant that the two surfaces could not be satisfactorily merged. Surface matching was again utilised, using the Isaac and Kaza 3D models as large control patches to recover the orientation of the aerial DEM

(Figure 3). Because of the ill-posed nature of the least squares solution (Besl and McKay, 1992), a good initial approximation was necessary; however, this was provided by the aerial triangulation using GCPs. Surface gradients in all primary directions were essential but, again, were present in the general ruggedness of the terrain and the steep cliff slopes. Close surface representations were expected between the two data collection methods because of the low amount of vegetation, the smooth, glacier-polished outcrop surface, and the lack of anticipated change over the five-year period between data acquisition periods (minimal erosion to rocks).

PolyWorks was again used to match the datasets, resulting in a mean error between the aerial DEM and the laser scanning DEMs of -0.002 m, with a standard deviation of 0.392 m. The errors assumed a normal distribution. Because of the sparser point spacing in the aerial DEM, large interpolation errors were more apparent where relatively small details (such as surface boulders and other debris) were not represented, as well as in sharp changes in slope (Figure 4). The remaining errors were acceptable when considering the two quite different surface modelling methods, as well as the distribution of the control patches. Despite this, results were within the tolerances allowed by the geology application. As the final stage of the modelling and registration process, the laser scan models and the transformed aerial DEM were merged into a single mesh. The laser scan triangles replaced the aerial DEM in areas of overlap to account for the higher accuracy of this data collection method.

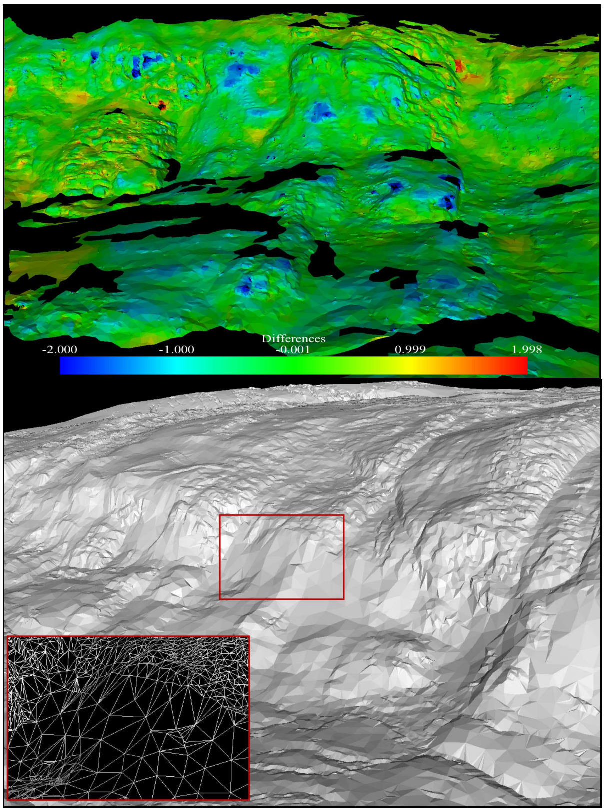

Figure 4. Top: Differences (in metres) between aerial and terrestrial models after surface matching, with colour scale ranging from blue (aerial under laser) to red (aerial above laser). Bottom and inset: Aerial DEM showing large and sparse triangles in cliff section.

5. TEXTURE MAPPING AND VISUALISATION

The final stage in the preparation of the virtual outcrop model was to map the aerial and terrestrial imagery onto the 3D mesh, important for carrying out geological interpretation. Because of the smooth outcrop surfaces and the regular weathering of the cliff sections, much geological detail could be present where little or no topographic detail was present.
Using the known image orientations and positions, triangle vertices could be projected into the imagery using the collinearity condition (Wolf and Dewitt, 2000) to determine image coordinates of the texture patches. The images were undistorted using the camera and lens parameters. It is often the case that for each triangle in the surface model, a number of images are available to choose from to define the texture patch. In this eventuality, the most suitable image was chosen using the angle between the triangle normal and the image ray, the area of the triangle in image space, and the distance between the camera position and the triangle (Debevec et al., 1996; El-Hakim et al., 1998). The ideal case would result in the aerial imagery being chosen for those triangles most horizontal, i.e. on the top and bottom of the cliffs, while the terrestrial imagery would be chosen for the cliff face triangles. In reality, a readjustment of the texture map was required to ensure that individual or small patches of triangles were not isolated, as imperfect registration or radiometric correction lead to disturbance when carrying out geological interpretation. The readjustment was carried out by ensuring that triangles sharing an edge were, where possible and appropriate, assigned to the same image (El-Hakim et al., 1998). Further work on increasing the realism of the texture-mapped model, such as radiometric correction, would facilitate the geological interpretation.

The outlined approach ensured that most of the triangles on the cliff sections were textured with images from the ground, whilst the remainder were textured using the aerial images. The result was a single photorealistic model, combining the techniques of photogrammetry and terrestrial laser scanning (Figure 5). From Figure 5 it is apparent that the laser data and terrestrial imagery add higher resolution to the cliff sections, enabling more detailed measurements to be made.

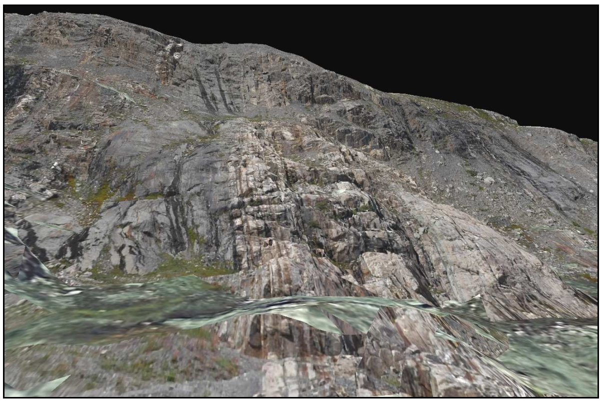

Figure 5. Textured model of Isaac cliff section. Approx. 100 m lateral extent.

6. RESULTS: GEOLOGICAL MODELLING

The Castle Creek model was used as the basis for geological interpretation and modelling. Other project data could be visualised simultaneously within a stereo 3D environment, allowing new angles of view. The value of such a setup for teaching purposes is readily apparent, as students can see the area before and after field trips to become familiar with the geology and perform analysis.

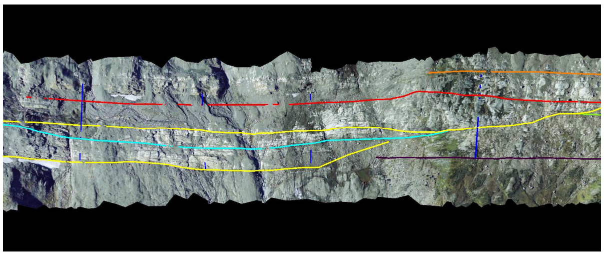

Figure 6. Top: Lines interpreted onto the textured 3D model (plan view; approx. 600 m × 100 m).

The Isaac Channel 3 area was studied as a detailed test case for the methodology. This area was cropped from the complete model, to save on computing resources during processing and visualisation. Then, 3D lines corresponding to key stratigraphic layers were digitised directly onto the outcrop model (Figure 6). Such lines form the spatial constraints for defining a geological volume. Combining the lines with the geologists' interpretation allowed 2.5D grid surfaces to be reconstructed by interpolation and extrapolation, using IRAP Reservoir Modeling System (RMS; Roxar, 2009). Such a procedure is prone to uncertainty, as the extension of surfaces into the outcrop is reliant on extrapolation. However, using trends from the survey data, as well as geological knowledge, this uncertainty can be evaluated. Prior to creation of such surfaces, the lines were transformed 95° around an axis parallel to the layering, so that the near-vertical layers could be restored to a horizontal (depositional) setting. For quality control, the surfaces were transformed back to their original positions and visualised with the textured model. The intersections between the surfaces and the 3D model were used to check the success of the surface gridding (Figure 7).

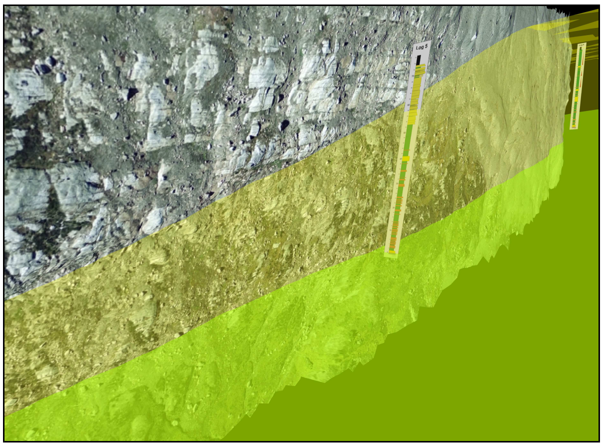

Figure 7. Two digital surfaces (yellow and green) visualised simultaneously with the textured outcrop model and geological logs recording the rock composition (vertical bars). The view is rotated so that the outcrop layers are close to their depositional orientation.

The generated surfaces defined the geological volume of the channel and levee units within the model, which would have been difficult to model without the accurate spatial data. The space between any two surfaces represented zones, which were gridded in 3D and voxels populated with a stochastic representation of the outcrop rock types (Figure 8). Such a model may be examined statistically to analyse connectivity between the various packages, as well as by running flow simulation experiments.

7. CONCLUSIONS

Terrestrial laser scanning and digital aerial photogrammetry were combined to create a digital elevation model of the Castle Creek outcrop, British Columbia, Canada. The integration of the two techniques proved to be essential to capture both the large outcrop surface and the near-vertical cliff sections which were essential for being able to recreate the 3D orientation of geological surfaces. Use of surface matching allowed the aerial photogrammetric DEM to be accurately registered, without the problems of collecting a conventional photocontrol point arrangement in a rugged and remote area. Texture mapping with aerial and terrestrial images resulted in a photorealistic model that could be used by geologists for interpretation, education and quantitative analysis. This model demonstrated the application of geomatics for geological outcrop analogue modelling, allowing the spatial accuracy and resolution to be enhanced. A geocellular volume was created from digitised features, which will be used by geologists to improve the geological understanding of the Castle Creek outcrop.

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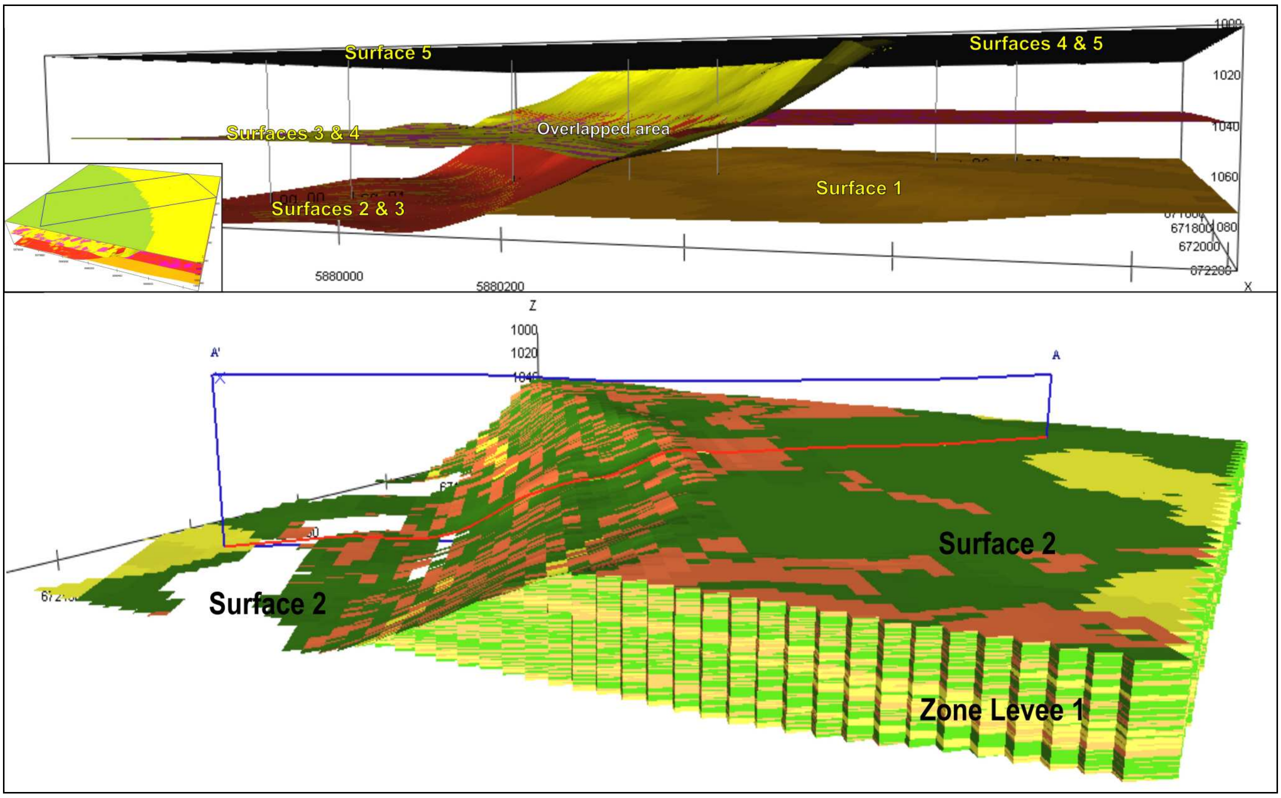

Figure 8. Top: 3D surfaces created from line data in reservoir modelling software (side view with structural rotation). Bottom: geocellular model of the Isaac Channel 3 area, created using the digitised surfaces (size of model c. 1200 × 1000 m; vertical exaggeration 2.1).

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