Combining Aerial Photogrammetry and Terrestrial Lidar for Reservoir Analog Modeling

Simon J. Buckley, Ernesto Schwarz, Viktor Terlaky, John A. Howell, and R.W. (Bill) Arnott

Abstract

High-resolution aerial photography was captured covering a geological outcrop at Castle Creek, British Columbia, Canada. Here, for the purposes of hydrocarbon analog modeling, the outcrop was required to be accurately surveyed, so that key stratigraphic surfaces could be mapped in three dimensions. Because the outcrop strata were vertically orientated, these surfaces could be tracked over a wide area; however, to provide a true reconstruction of the geology, it was necessary to also model localized vertical cliffs providing a cross-section through the stratigraphy. Terrestrial lidar was utilized to cover these cliff sections which were poorly represented in the 2.5D aerial data. The integrated outcrop surface was textured with metric aerial and terrestrial imagery providing a photorealistic model that could be used for interpretation by geologists. This formed the basis for building a geocellular model of the geological volume, which was used to assist in the understanding of subsurface reservoirs where data are often limited.

Introduction

The use of digital spatial data collection techniques is becoming common within the geology discipline. In particular, studies of hydrocarbon outcrop analogs have recently begun to embrace techniques such as digital photogrammetry, the global positioning system (GPS), and laser scanning (Pringle *et al.*, 2004; Bellian *et al.*, 2005; Lebel *et al.*, 2007; Buckley *et al.*, 2008). Outcrop analogs give geologists first-hand experience of the depositional environments and geometric configurations of subsurface oil and gas producing reservoirs, and aquifers. Because the subsurface is normally inaccessible for study, except for disparate drilled well bores and geophysical measurements, outcrop analogs are used to improve the statistical modeling required when planning an extraction strategy for hydrocarbon production (Pringle *et al.*, 2006). Typically, a geocellular model is used to represent the reservoir or reservoir analog volume. Such a model integrates geometrical, geophysical, and geological interpretation into a computer-based realization of the subsurface. The geometry of geological features (for example, stratigraphic surfaces and faults) constrains the model in space, while grid cells (voxels) are assigned properties relating to the geology, porosity, permeability, and fluid saturations. Fluid flow simulation can then be used to assess the production potential of the geological volume and the impact of different heterogeneities and well distributions upon the recovery from the oil field. In recent years, geocellular models of reservoir analogs have been generated combining geometrical configurations and sedimentological attributes extracted from outcrop data and petrophysics from reservoirs (e.g., Enge *et al.*, 2007). The contribution of geomatics techniques within this scenario is by providing high-resolution and accurate geometry for constraining the geocellular model. In addition, the creation of virtual outcrop models gives a three-dimensional environment for interpretation, analysis and education which, combined with traditional field data, is of extreme value for the geologist (Lebel and Da Roza, 1999; Banerjee and Mitra, 2004). Higher resolution spatial data allows more detailed studies to be carried out at a variety of scales, and in a more quantitative manner than possible using traditional field techniques alone (Enge *et al.*, 2007).

Criteria for outcrop selection are based on the similarity of the analog processes and geology within the subsurface reservoir, the degree of exposure, and the "three-dimensionality" of the outcrop, as well as more practical issues, such as vegetation cover and accessibility. The amount of three-dimensional exposure is critical for being able to recreate the geological volume (Bryant *et al.*, 2000; Pringle *et al.*, 2004; Enge *et al.*, 2007), and the outcrop must have surfaces exposing the geology along the dip direction (Groshong, 1999). Without this, it may not be possible to determine the geometry of key stratigraphic surfaces behind the outcrop face, increasing uncertainty in the resultant model. For subsurface reservoirs, where 3D seismic data are available, surfaces may be tracked over large distances in all directions; however, for outcrop data where surfaces disappear below, or are eroded above, the ground, recreating surface geometry is more challenging. In this case, the available

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three-dimensionality is used to constrain the modeled geological volume, using lines and points digitized on the outcrop to act as guides for extrapolating surfaces behind the outcrop faces. Coupled with this is an extensive conceptual geological model of the system, developed using traditional fieldwork, which is used to assist with surface recreation.

The introduction of terrestrial laser scanning (lidar) has had a large impact on the study of outcrops, as the rapid, precise data acquisition of the active laser sensor allows topography to be captured without the relatively complex and time consuming processing workflow of close-range digital photogrammetry. The associated uncertainties in automated terrain extraction, caused by a complicated surface or low image texture, are also removed, making the procedure attractive for non-specialists. This has been seen in the recent growth of applications and literature related to laser scanning in geology (Bellian *et al.*, 2005; Sagy *et al.*, 2007; Buckley *et al.*, 2008).

This paper reports on research combining two techniques, digital aerial photogrammetry and terrestrial laser scanning, for creating a high-resolution photo-realistic model of a large outcrop occurring at Castle Creek, east-central British Columbia, Canada. The site is characterized by vertically-dipping layers, a result of compression and uplift during the building of the mountain belt within the southern Canadian Cordillera, where the study area is located. The integration of the two methods was therefore required: aerial photogrammetry to model the overall outcrop surface, and terrestrial lidar to develop the third dimension at localized cliff sections providing a cross-section through the stratigraphy. The model was then used as the basis for interpretation and digitization of geological surfaces, allowing the recreation of the geology within a geocellular model.

Background to the Castle Creek Study Area

The Castle Creek study area is situated in the Cariboo Mountains, east-central British Columbia, Canada. These mountains form part of the southern Canadian Cordillera, an extensive orogenic belt that borders the western margin of Canada and was built mainly during the Mesozoic (Ross *et al.*, 1995). At Castle Creek, a 2 km-thick succession of sandstones and mudstones belonging to the Neoproterozoic Windermere Supergroup crops out (Figure 1). The present day strata dip near-vertically, as they have been rotated approximately 95° during uplift from the near-horizontal setting in which they were originally deposited (Ross and Arnott, 2008). Additionally, due to the relatively recent retreat of the Castle Creek glacier, the outcrop surface is polished and largely free of vegetation. This allows geologists to track key stratigraphic surfaces and bed packages laterally for hundreds of meters, while the stratigraphy can be followed up uninterrupted for over two kilometers (Figure 1). This is in sharp contrast to many analog studies, which may be limited in terms of stratigraphic thickness by the height of cliffs or depth of quarrying, as well as areal extension provided by outcrop exposure.

The succession exposed at Castle Creek is interpreted to represent deep-marine sediments deposited mainly by turbidity currents in a passive (continental) margin, and is collectively known as the Windermere Turbidite System (Ross

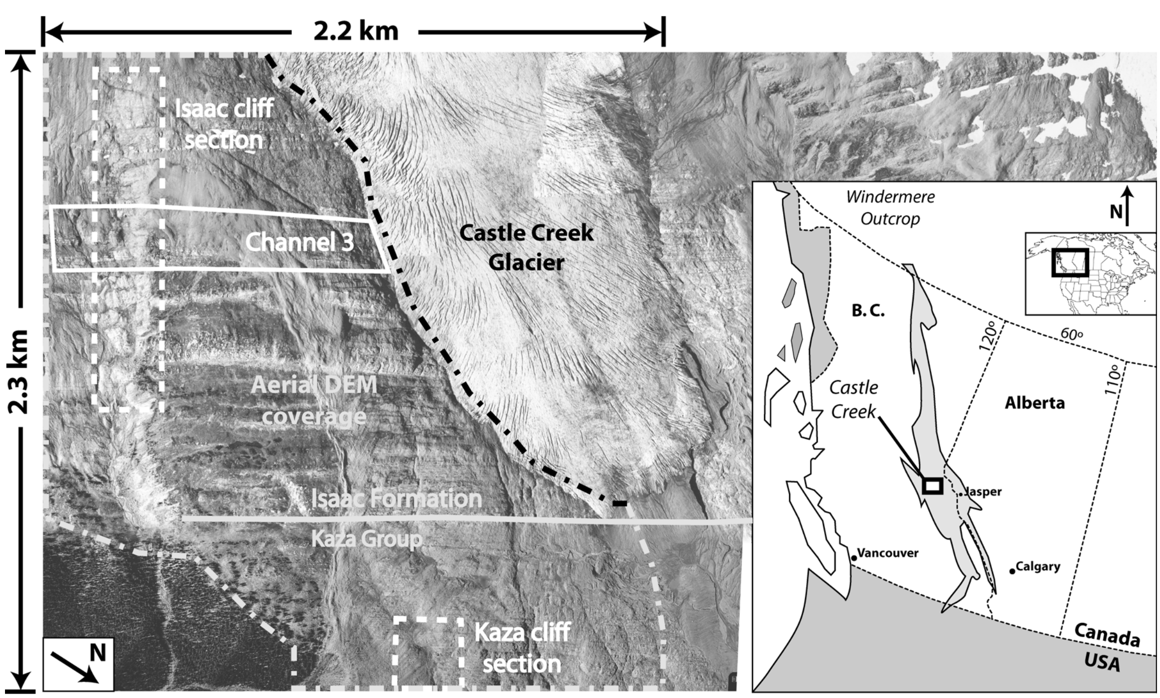

Figure 1. Aerial photograph mosaic of Castle Creek, British Columbia, Canada, showing extents of the geological area, the stratigraphic units of the Windermere Turbidite System and the location of the Isaac Channel 3 section. Also shown is the coverage of the DEM created from the stereo aerial photography (dashed-dotted line) and the location of cliff sections scanned using terrestrial lidar (dashed lines). Inset: location map showing the extent of the Windermere Turbidite System (after Ross, 1991).

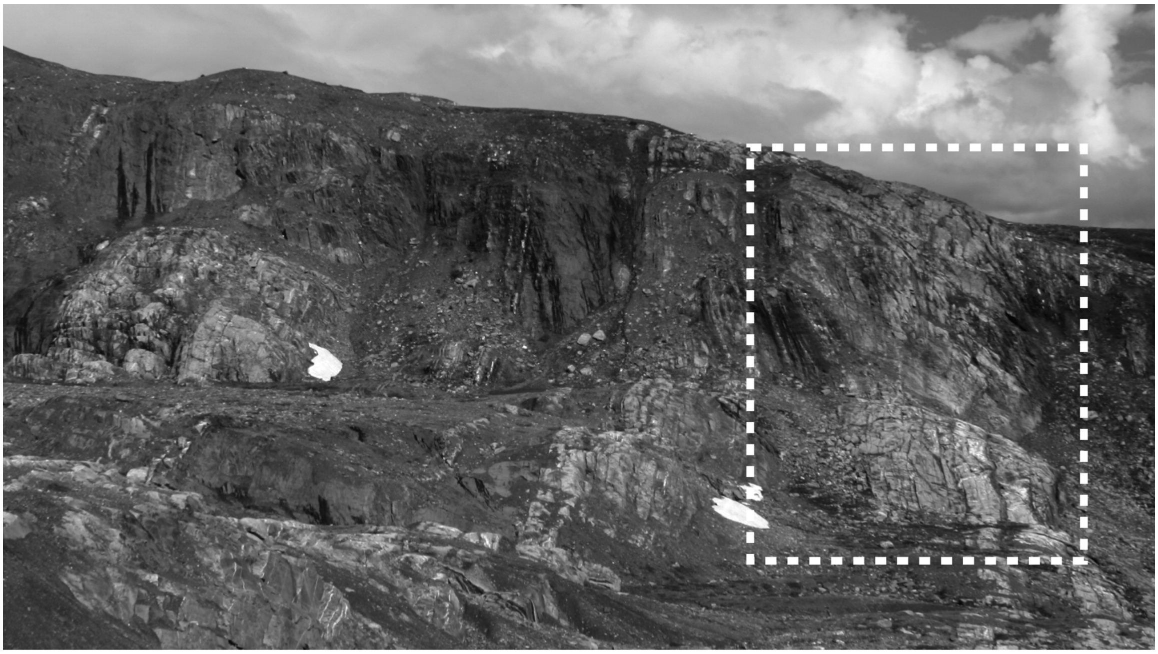

Figure 2. Cliff section exposing channel bodies of the Isaac Formation, as photographed from the ground (cliff height: approximately 90 m). The Isaac Channel 3 study area is highlighted.

and Arnott, 2008). The Kaza Group at the bottom of the section is composed of sandstone-dominated, sheet-like to poorly-channelized deposits interpreted to represent a basin floor setting (Ross and Arnott, 2008). The overlying Isaac Formation comprises six major, laterally extensive (kilometer-scale), sandstone-rich units surrounded by thin-bedded, mudstone-rich strata and debris-flow/slide complexes, interpreted to represent slope deposition (Schwarz and Arnott, 2007; Ross and Arnott, 2008). These deep-marine deposits are relevant because of current hydrocarbon exploration and development being conducted in similar continental-margin basins, such as offshore Brazil, West Africa and the Gulf of Mexico (Schwarz and Arnott, 2007).

This particular study focused on a detailed subset of the Castle Creek area, with the aim of modeling part of a single large channel body as a geocellular volume. This area (marked on Figure 1; Figure 2) was termed Isaac Channel 3 and represents one of six major sandstone-rich channel units present within the Isaac Formation at Castle Creek (Navarro *et al.*, 2008). This unit provides geologists with the opportunity to study well-exposed channelized deposits and laterally adjacent levee and overbank deposits, as well as acting as an analog for modern turbidite settings (Navarro *et al.*, 2008). The size of the Isaac Channel 3 area was approximately 1,100 m by 100 m and, like the Castle Creek area as a whole, consisted of a well-exposed 2D section. For this study, it was aimed to be able to map the relative position of key geological surfaces with a precision of around 0.3 m over the outcrop extent.

Technique Selection

The near-vertical orientation of the layers means that the outcrop stratigraphy is exposed effectively as a two-dimensional cross-section. Because of the lack of vegetation on the outcrop surface, a method such as digital aerial photogrammetry or airborne laser scanning would have been suitable for acquiring topographic data. However, the relatively smooth outcrop surface, and the requirement for high-resolution imagery for geological mapping meant that aerial stereo-photography was the preferred method for terrain modeling. In addition, as part of earlier work on the Castle Creek outcrop, high-resolution aerial photography had already been captured and was available for photogrammetric processing (Schwarz and Arnott, 2007).

For the Isaac Channel 3 study area, a certain amount of three-dimensionality was present in the topographic undulation of the outcrop surface. However, near-vertical cliffs (up to 100 m high) occurring in the Castle Creek area, and across the study section (Figure 2), offered the opportunity to model more detailed profiles through the outcrop. Although the aerial photogrammetric data gave excellent coverage of the outcrop surface, little 3D information was present for the modeling of the volume. Vertical aerial photography allows only a 2.5D representation of the terrain, which was insufficient for this study, where extra detail in the cliffs was required. Therefore, a terrestrial laser scanner equipped with a digital camera was used to acquire higher resolution terrain data covering selected cliffs, which allowed the continuation of the geological surfaces in the dip direction into the outcrop (Figure 3) to be retrieved. In this way, the two techniques were complementary, with the aerial data giving more 2D coverage of the whole area where less accuracy was required in mapping the various layers, and the laser data gave increased accuracy and allowed the interpretation of more subtle details of the 3D geometry.

Data Collection Methodology

Aerial photography had been flown in summer 2001 using a calibrated Zeiss RMK TOP30 camera equipped with a 300 mm lens (calibrated $f = 304.953$ mm). With a flying height of

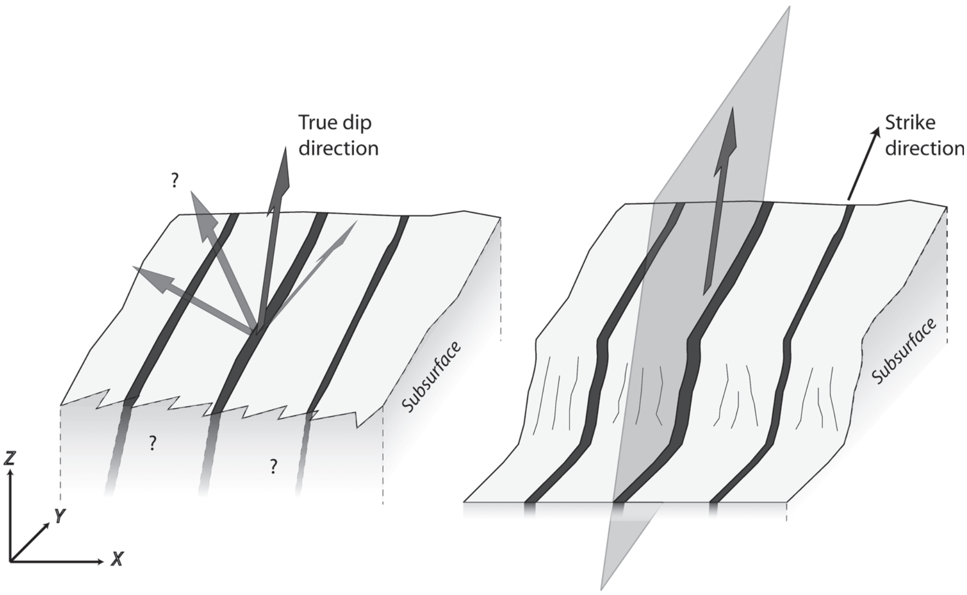

Figure 3. Diagram showing the requirement for three-dimensional exposure when attempting to model a geological outcrop: (a) Terrain surface with low relief, and (b) Additional relief creates a cross section through the geology in the dip direction, allowing the orientation of layers to be measured.

around 3,300 m (10,827 ft) ASL and an average ground height of 2,000 m (6,562 ft) AMT, this configuration resulted in a photo scale of approximately 1:4000. The overlap between adjacent photographs was 70 percent and sidelap of 10 percent. The area highlighted in Figure 1 was chosen for digital elevation model (DEM) extraction, equivalent to the main geological study area in Castle Creek South (approx. 2.2 km $\times$ 2.3 km). Within this area were two cliffs where geologists carried out detailed sedimentological fieldwork, i.e., the Kaza section at the base of the stratigraphy and the Isaac section that contained the Isaac Channel 3 area. The DEM extraction area was covered by 12 photographs in three strips. Prints of the aerial photography had previously been used by geologists for assisting with field correlation and mapping of the various layers across the outcrop (Schwarz and Arnott, 2007; Navarro *et al.*, 2008). On commencement of this stage of the project, the set of photography was scanned at 13 μm resolution, resulting in a ground pixel spacing of approximately 0.1 m.

Terrestrial laser scanning was carried out in August 2006, for collection of topographic data covering the Kaza and Isaac cliff sections. A Riegl LMS-Z420i laser scanner was used for this work (Riegl, 2009). With a maximum range (based on the reflectance of natural rock targets) of around 650 m, quoted point accuracy of 0.01 m, and point acquisition rate of up to 12,000 points per second, this scanner was ideal for capturing the Castle Creek cliff sections. The Isaac section (containing four large sandstone-dominated channel units, including Isaac Channel 3) was 900 m long, 200 m deep, and up to 90 m high (Figure 2). The smaller Kaza cliff section was 450 m long, 170 m deep and up to 50 m high. A calibrated Nikon D100 six-megapixel camera was mounted on the laser scanner, providing high-resolution digital images that were registered to the scanner coordinate system by means of a calibrated rigid mounting transformation (Jansa *et al.*, 2004). Nikkor 85 mm and 50 mm lenses were used for the Isaac and Kaza sections respectively.

The Isaac section required six scan positions to cover the length of the cliff, while the shorter Kaza section required four, including at least 20 percent overlap between adjoining scans. The average point spacing was 0.1 m for both areas. At each position, imagery was also taken with the digital camera for use later on for building a textured 3D model of the outcrop, and for assistance with geological interpretation. The camera was also operated handheld so that images could be taken from an optimal angle to the cliff, as best results for the texturing were obtained when the camera orientation was closest to normal to the outcrop (e.g., Debevec *et al.*, 1996). These images were registered to the project coordinate system by space resection, using manually identified tie-points between corresponding natural features in the image and laser data. The average standard deviation for the resection was around 1.5 pixels.

The terrestrial scan data were registered with GPS using an antenna mounted on top of the laser scanner recording data for the duration of the scan position setup. Data were post-processed relative to a base station operating within the confines of the study area. The base station coordinates were determined using precise point positioning from three days of observation. This GPS configuration provided the Universal Transverse Mercator (UTM) Zone 10 positions of the scanner centers, with standard deviations of the processed baselines better than 0.1 m in the horizontal and vertical directions.

Surface Modeling and Data Registration

A limited number of natural ground control points (GCPs) had been previously collected using real-time kinematic GPS, though because of the remoteness of the field area and problems with accessibility caused by the difficult terrain, the number and distribution was not optimal for performing an accurate aerial triangulation for the whole block of 12 photos (Wolf and Dewitt, 2000). An alternative approach to integrating the two datasets was therefore adopted, using the GCPs to give an initial block orientation, which was then refined using a surface matching approach. This initial orientation resulted in the correct relative orientation, but with an error in the external orientation corresponding to the limited quality of the photo-control points. Comparison between the initial aerial DEM position and the lidar data revealed up to 5 m of difference in areas of overlap corresponding to the cliff sections. A triangular irregular network (TIN) DEM was extracted from the orientated image data, with additional breaklines manually measured along sharp changes in surface gradient. The processed photogrammetric DEM consisted of close to 460,000 triangles, with an average point spacing of 3 m, which was sufficient to represent the relatively smooth outcrop surface.

The raw lidar point clouds were registered using a surface matching approach in the PolyWorks® software by InnovMetric Software, Inc. Overlap between the scans was minimized in a least squares adjustment to recover the transformations relative to a fixed scan in the center of the cliff section (see e.g., Besl and McKay, 1992, for details on surface matching). The main advantage of this approach over the more conventional use of control points sited on the outcrop face is the reduction of expensive field time. Additional advantages are found in the redundancy of using all available data, especially on this outcrop where there was almost no vegetation; and the ability to quantify mismatch between the overlap areas, indicating the success of the solution (Buckley and Mitchell, 2004). Once all scans were matched to a common coordinate system, the scan centers were transformed to the UTM coordinate system using the GPS scanner center positions and 3D conformal transformation (with Root Mean Square Error of 0.060 m).

The raw point clouds were merged and filtered to reduce the point density in overlap areas (Buckley and Mitchell, 2004). However, further reduction was necessary before a triangle mesh could be created, as with 3.5 million points, this was still too many to be easily meshed and visualized without specialized hardware. An advantage of laser scanning is the collection of point clouds that may be of a higher density than required by the current application, but may be useful for posterity to allow the data to be revisited for further, unanticipated purposes. The merged point clouds were reduced by calculating the normal distance between each point to a plane formed by the neighboring points, where a distance lower than a tolerance of 0.05 m signaled insignificant contribution to the topography. The flagged points were eliminated and the remainder triangulated to form 3D meshes. The resulting meshes contained 1.1 million triangles for the Isaac section and 500,000 triangles for the Kaza section, with average point spacing of 0.4 m.

Once triangle surfaces had been defined for both the aerial and ground-based datasets, surface matching was again employed to recover the transformation that would minimize the differences between the two datasets. The two meshes derived from the laser scanning data (Isaac and Kaza sections) were used as large control patches, held fixed while the aerial DEM was allowed to move. Requirements for a successful solution are for gradients to exist in different directions on conjugate surfaces, and for there to be enough similarity between the surfaces to ensure good correspondence, even when removing outliers (Besl and McKay, 1992). Too much noise or difference between the datasets would strongly influence the least squares procedure, resulting in poor solutions being found. In this case, surface gradients were provided by the relief in the general outcrop topography, especially in the steeper cliff sections. Because of the glacier-scoured outcrop surface, little difference in sampling between the aerial and ground-based terrain models was expected. In particular, only small amounts of localized change would have occurred, despite the five year gap between the two datasets being captured. This was anticipated to have been limited to small differences in vegetation and distribution of snow patches. The surface matching problem is ill-posed (Besl and McKay, 1992); therefore reasonably close initial approximations are a requirement for the solution to converge. In this case the exterior orientation of the photogrammetric block provided by the GCPs was sufficiently close to act as an initial approximation.

A potential problem in matching may have arisen due to the different sampling strategies of the two measurement systems. Because the aerial photogrammetry measured a 2.5D surface, flat areas would be well covered and cliff sections poorly recorded; in contrast, the terrestrial laser scanner recorded cliff sections well, but was limited in coverage of the surrounding topography due to the deflection angle to horizontal surfaces brought about by the low field of view of the instrument. However, examination of the terrestrial models showed that a sufficient amount of data was present below and above the cliff faces in the two areas (e.g., Figure 4a).

Convergence of the matching algorithm was achieved, with the resolved transformation parameters improving the integration of the two datasets. Differences between the two surfaces were found by calculating the normal distance between each triangle centre in the lidar DEM to the aerial DEM (Figure 4b). This revealed a mean error of −0.0018 m and a standard deviation of 0.3919 m, with errors following a normal distribution. This was around the level of error expected, as the more sparsely sampled aerial surface was prone to interpolation error during comparison with the lidar surface, especially in areas of sudden topographic change where some larger errors existed. In addition, features too small to be sampled by the aerial DEM (less than the point density), but of significance in the lidar model, such as surface debris, are apparent in the difference map (Figure 4b). Although the distribution of the two control patches relative to the whole DEM was relatively poor compared to conventional GCPs, the results of the matching showed good agreement between the two models. Results for the Isaac section are shown in Figure 4, with similar results obtained for the Kaza section.

Texture Mapping

Once surface matching was performed, the aerial and lidar models could be directly utilized in a single coordinate system. However, for being able to visualize, interpret and perform quantitative analysis on the geology, it was necessary to first integrate the DEM data with the aerial and terrestrial imagery (e.g., Forkuo and King, 2004). Because of the glacier-polished rock surface, the outcrop surface contained much geology that could not be distinguished by changes in topography. Hence, texture mapping was performed to add geologic information to the dataset. The models from the Isaac and Kaza sections were merged with the aerial DEM to create a single 3D mesh, with the higher accuracy lidar triangles replacing the aerial data in areas of overlap. Rectification of the aerial and ground-based imagery was carried out to remove the effects of lens distortion prior to texture mapping. Because the camera orientation and position was known for each image, triangle vertices could be projected into the imagery to determine image coordinates of the texture patches (Wolf and Dewitt, 2000). Where multiple images were available for a single triangle, parame-

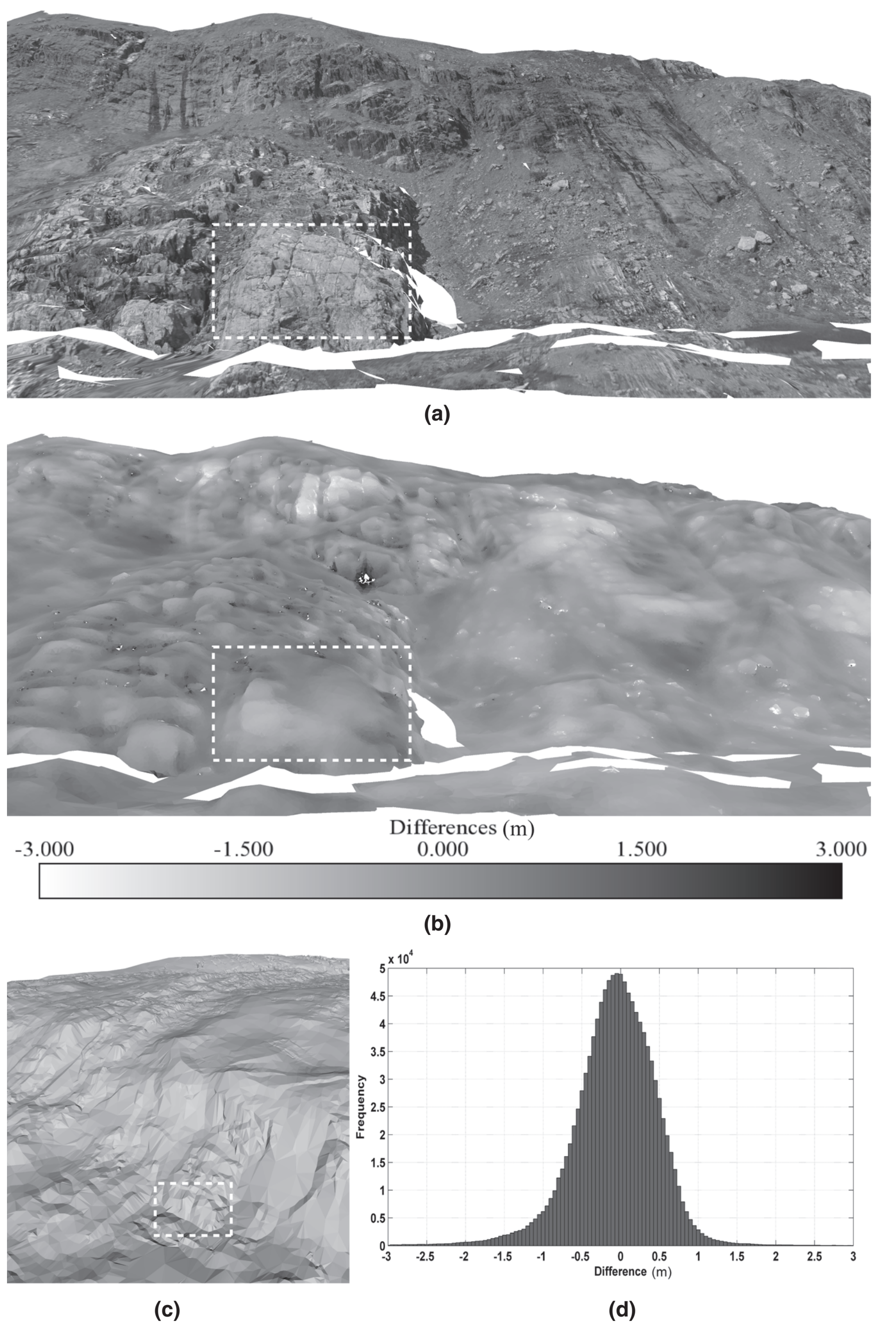

Figure 4. Post-registration differences between the terrestrial lidar and aerial photogrammetric surfaces for the Isaac cliff section: (a) Textured lidar model, (b) Lidar model colored with difference map, (c) Oblique view of aerial photogrammetric DEM, showing the low triangle resolution in steep areas of the cliff (corresponding areas are marked in (a), (b) and (c)). Height of section is approximately 90 m, and (d) Histogram of differences.

ters based on the angle between the triangle normal and the image ray, the area of the triangle in the image, and the distance between the camera and the triangle were used to select the most suitable image to use (Debevec *et al.*, 1996; El-Hakim *et al.*, 1998). A second adjustment of the triangle-image map was then performed to ensure that where possible adjacent triangles were mapped using the same image (e.g., El-Hakim *et al.*, 1998). For interpretation, it is distracting to have regions of single or few triangles mapped with different images, as radiometric and geometric distortions can detract from the geology.

Because of the different view directions of the aerial and terrestrial imagery, the texture mapping parameters described above ensured that most triangles on the cliff sections were textured with images from the ground, while the remainder of the merged model was textured using the aerial photos. The result was a single model of the Castle Creek outcrop comprising the two data collection methods (Figure 5). The

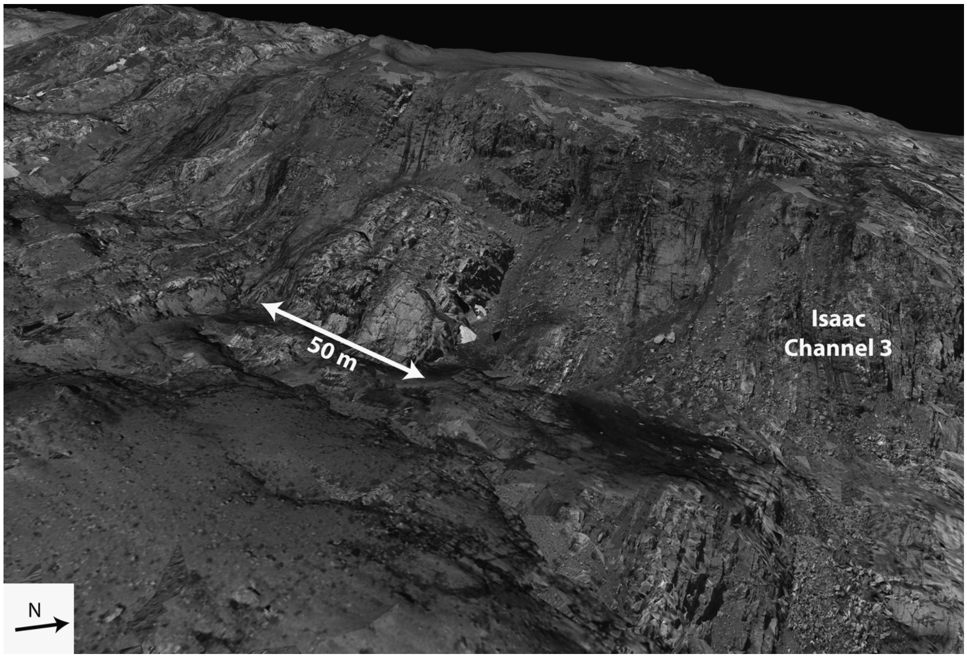

Figure 5. Final outcrop model of part of the Isaac cliff section comprising merged photogrammetric and lidar terrain data, and texture-mapped with aerial and terrestrial photographs.

use of lidar and close-range imagery adds high resolution to the cliff sections, enabling more detailed study of the outcrop in the depth direction, as it enters the subsurface. This result, combined with the extensive aerial coverage of the 2D outcrop stratigraphy, enhanced geological interpretation.

Geological Modeling of the Isaac Channel 3 Section

The virtual outcrop model for the Castle Creek area provided a base for integration of project data, including field measurements and sedimentary logs, i.e., *cross-sections* through the outcrop where the geologist records rock attributes bed-by-bed along a measured line. Particularly important was that it was possible for geologists to visualize the data using 3D viewing software and a stereo display, allowing new angles of view, and an appreciation of the area as a whole, i.e., interpretations not possible in the field or with aerial photo prints. In addition, the combined model could be simultaneously viewed at various scales: the aerial data used for the wider area, while more details could be gained in the cliff sections (where much conventional geological fieldwork had been carried out) by zooming-in to these areas. Using this virtual outcrop model, a geo-model was built for the Isaac Channel 3 detailed study area using the methodology outlined in Enge *et al.* (2007).

First, the area of interest was cut out of the overall model, to save on computer hardware resources during visualization. Then, 3D lines corresponding to the key bounding stratigraphic surfaces from the deep-marine channel fill and overbank/levee units were interpreted and digitized directly on the virtual outcrop model (Figure 6).

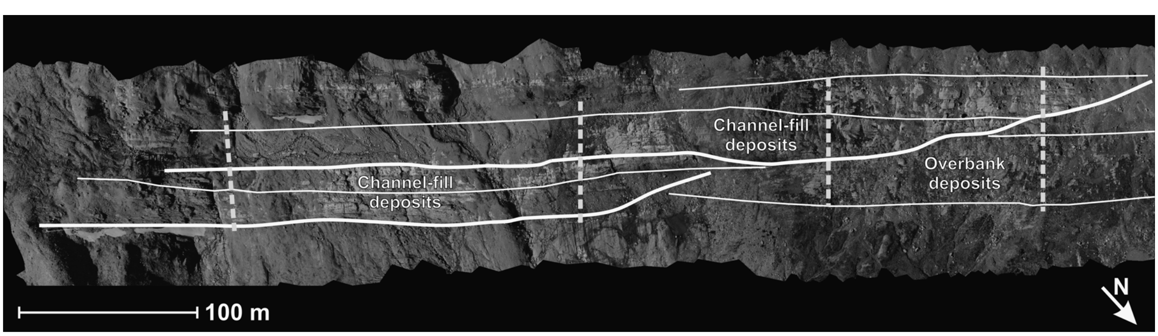

Figure 6. Plan view showing selected lines interpreted and digitized onto the virtual outcrop model. Dashed lines are locations of the sedimentary logs where rock attributes are measured bed-by-bed in the field. Note the cross-sectional channel shapes (marked by thicker lines). D-1 to D-4 indicate four main depositional stages from oldest overbank deposits to youngest channel-fill deposits.

These lines formed the spatial constraints for the geological volume, which were combined with the geologists' conceptual model (Navarro *et al.*, 2008) for extrapolating geological surfaces. Geo-models from outcrop data are typically used to examine the effects of different geological heterogeneities on numerically simulated fluid flow. These heterogeneities may include the lateral and vertical stacking of deep marine channels, in which the material in the channel-fill deposits is typically permeable while the clays that were deposited outside the channel are typically not, and provide barriers to hydrocarbons moving through the reservoir. In most reservoir cases the beds are sub-horizontal or gently tilted; however as the Castle Creek outcrops had been uplifted during mountain building it was necessary to remove the tilt of the outcrop. A simple rotation of 95° around an axis parallel to the strike of strata was applied using structural restoration software (3DMove; Midland Valley Exploration).

The structurally-restored lines were imported to a reservoir modeling package (Irap RMS; Roxar ASA), software which is used primarily by the petroleum industry for modeling subsurface reservoirs, using data such as seismic and well cores, and planning strategies for hydrocarbon extraction. The software allows the integration of many forms of spatially-referenced geological data in a common environment. The lines were used as guides to assist in the creation of 2.5D grid surfaces representing the key geological layers, using a b-spline algorithm to extrapolate the data away from the actual outcrop face (Figure 7). There is potential during this procedure for large amounts of error to be introduced, both from the choice of extrapolation technique, as well as the limited amount of input data used. This is where geological understanding is critical, as well as the accuracy of the spatial data. In this case, lines mapped using the virtual outcrop data were of high enough accuracy to recreate the subtle dips between the layers. Quality control of the generated surfaces was carried out by removing the structural rotation to the surfaces and displaying them simultaneously with the 3D textured model (Figure 8). In this way, the intersection of the surfaces with the digitized lines on the outcrop model revealed the success of the surface gridding, at least where an exact match should have existed. In addition, the overall trend of the surfaces away from the outcrop face could be checked.

The generated surfaces define the geological volume that bound different channel and levee units within the model. The terraced, composite surfaces at the base of the channel-fill units (Figures 6 and 7) would have been very difficult to recreate without the aid of the 3D data. The space between two surfaces represented modeling zones, which were gridded in 3D and populated with a stochastic representation of the lithofacies (Figure 9). Facies modeling was heavily constrained by sedimentary log data imported as "wells" in the geomodel. Such a geocellular model may be examined statistically to determine connectivity between packages, as well as by running flow simulation experiments. Consequently, the geocellular model based on outcrop data can assist geologists' understanding of the processes and geometry occurring in the reservoir analog and may provide insights and input variables to build more realistic and accurate subsurface models of deep-marine turbidite-dominated reservoirs.

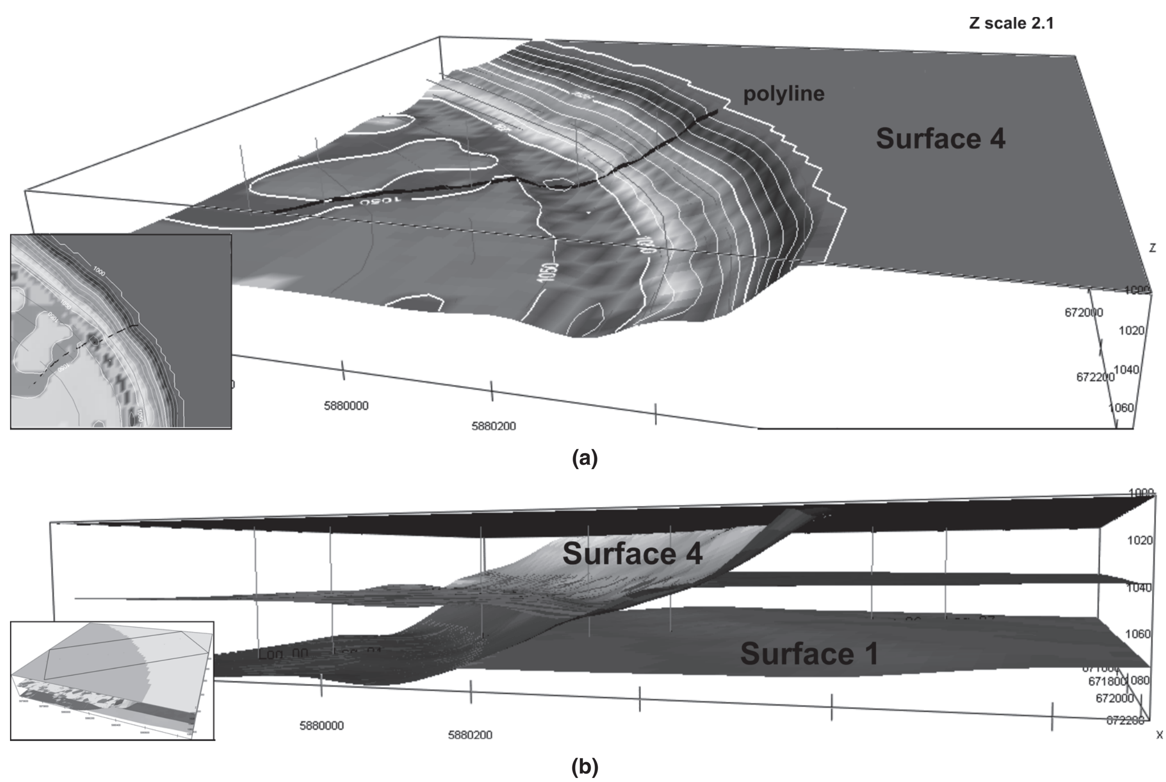

Figure 7. Key stratigraphic surfaces in reservoir modeling environment, with structural restoration applied: (a) Example surface created from digitized lines and geological knowledge. (b) Side view showing relative position of surfaces defining the modeling volume. Size of model is approximately 1200 m × 1,000 m, and the vertical exaggeration is 2:1.

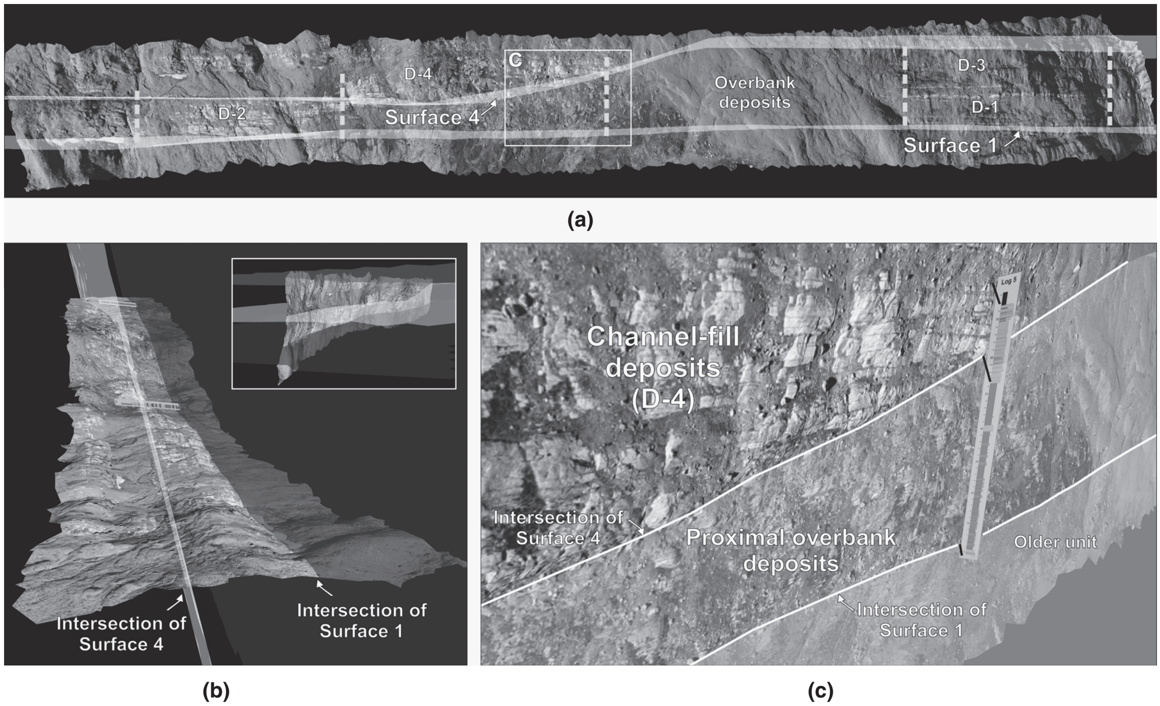

Figure 8. Digital surfaces representing geological layers created in reservoir modeling software from digitized lines, and with structural rotation removed so that they can be visualized simultaneously with the textured outcrop model (surfaces visualized with 50 percent transparency): (a) Plan view showing selected surfaces: a relatively flat basal surface (Surface 1) and a channel-cut surface (Surface 4). Compare with lines in Figure 6 (Outcrop section approximately 1,100 m $\times$ 100 m); (b) Perspective view (from west to east) of outcrop with same surfaces intersecting; inset shows outcrop section in structurally-restored view, and (c) Detailed view showing intersection of surfaces with outcrop and sedimentary log, viewed as if structural rotation existed.

Conclusions

The potential for digital spatial data collection techniques to contribute to and enhance geological outcrop modeling research is high, and has been demonstrated in this paper using an integrated data collection approach for modeling a large outcrop at Castle Creek, Canada. Because of the limited three-dimensionality of the outcrop, terrestrial laser scanning was used to augment a DEM derived from aerial photogrammetry, so that geological layers could be interpreted with high enough precision to extend the outcrop surfaces in the dip direction within a reservoir modeling package. The study shows that the presence of a high-resolution digital outcrop model serves as a framework for detailed interpretation and geological field data integration within a project, and is a valuable teaching asset. For the Castle Creek outcrop, this enabled a new appreciation of the spatial relationships between the channel bodies to be gained. The employment of geomatics techniques offers a more quantitative approach to outcrop geology, an area that is anticipated to grow in the future.

Acknowledgments

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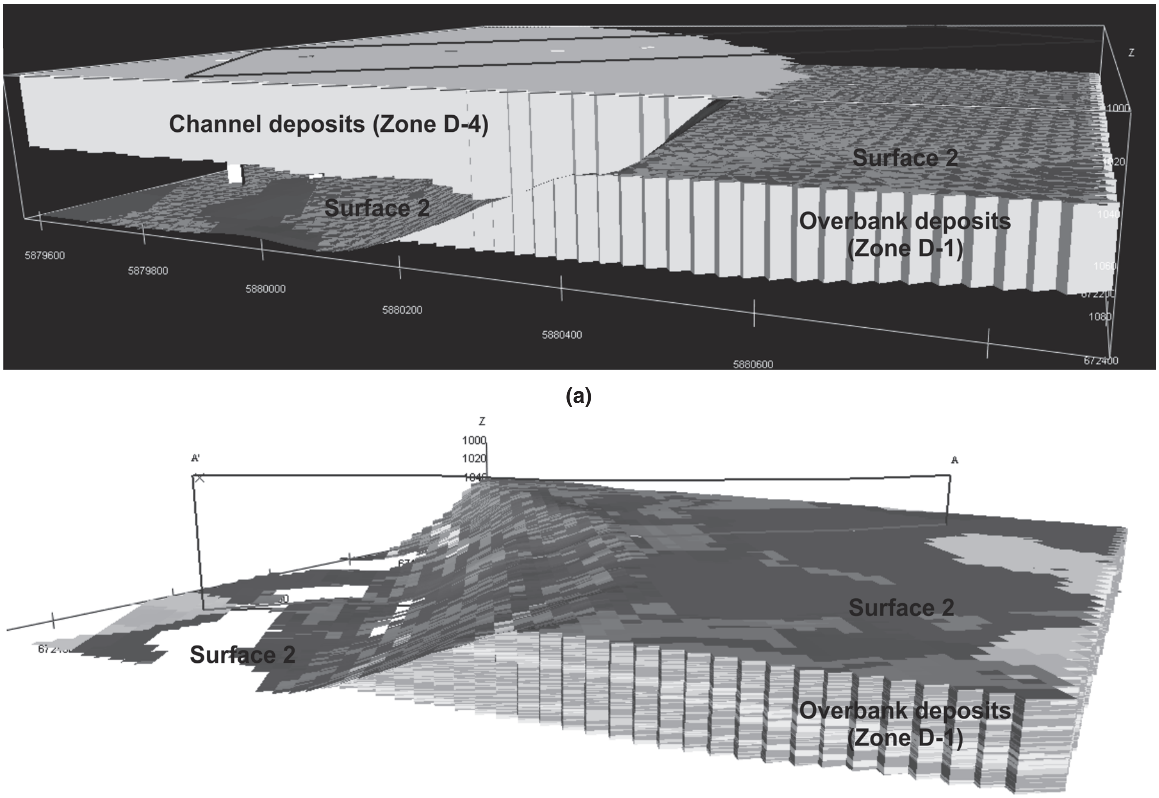

Figure 9. Geocellular model of Isaac Channel 3: (a) The volume between input surfaces is gridded, (b) Each cell is populated with representative rock types (facies), according to outcrop data and the geological interpretation (dark grey: thin-bedded turbidites; mid grey: medium-bedded turbidites; light grey: thick-bedded turbidites). Overbank deposits overlying Surface 1 and channel-fill deposits overlying Surface 4 are shown for illustration. Size of model is approximately 1200 m × 1000 m, and the vertical exaggeration is 2:1.

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