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Creating virtual 3-D outcrop

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Because of the high precision of present-day GPS and reflectorless laser technology, geologic information and remotely sensed data (i.e., seismic and GPR grids, wells) can be positioned accurately in 3-D and reconstructed as a virtual image. Hence, we have developed the "virtual outcrop" for applications that require knowledge about the 3-D spatial arrangements of rock types.

This article shows how we have applied digital methodology to geologic reconnaissance and in detailed outcrop mapping, including characterization of an outcrop as a reservoir analog where we merged detailed outcrop mapping with geophysical GPR survey data, wells, and stratigraphic sections.

Mapping is the foundation of the geologic sciences. The fact that specific observations are attached to specific geographic locations is critical in evaluating spatial and temporal relationships. The three basic elements necessary for a useful geologic map are location, lithologic information, and spatial or geometric relationships. Digital mapping is considerably more precise than traditional field methods and allows information to be gathered accurately in 3-D. It also allows data to be collected from remote or inaccessible locations, such as on vertical cliff faces. We have coined the term "cybermapping" to describe these techniques because they differ from typical GIS data bases which are built by digitizing hard-copy sources (e.g., paper maps).

GPS incorporates signals from multiple satellites to triangulate a position on the surface of the earth. The distinctive feature of GPS is that the location generated is "geocentric" (i.e., it is relative to the center of the earth). This means that measurements taken in one place can be directly compared to any other GPS position. The rapid development of this technology has produced significant cost reduction; an increase in capabilities; and faster, more "friendly" data reduction; in addition, it is considerably more precise than traditional field mapping in most cases. Consequently, the general user can generate precise locations much easier than even five years ago. A georeferenced location can also be determined in the field in real time. A single receiver positioning has a precision of approximately 100 m. Positioning of one receiver relative to another—"differential" positioning—can be as precise as 1 mm (with the carrier phase part of the signal) or 0.2-5 m (with the code phase part of the signal), depending on the type of receiver and method (See Table 1 in Aiken et al., *TLE*, January 1998). Real-time differential code phase positioning is instantaneous but at lower accuracy (decimeters to a few meters).

Commercial and government providers broadcast differential code correction signals through radio stations or even satellites at a cost that is very affordable. RTK, real-time kinematic GPS, employs a method of carrier-phase differential GPS positioning that provides the highest precision, centimeters in real time. However, the observer must operate the transmitting radio and GPS base station.

Another technological advance strongly influencing digital mapping is reflectorless laser surveying. Utilization of the "total station" has been common in many disciplines of the geosciences consisting of a laser range finder with corner reflector prisms, and horizontal and vertical angle measuring capabilities. Angular measurement error is in the range of 3-5 arc-s, resulting in an accuracy of 1-4 cm per km. The basic laser range finder parameters are pulse time of

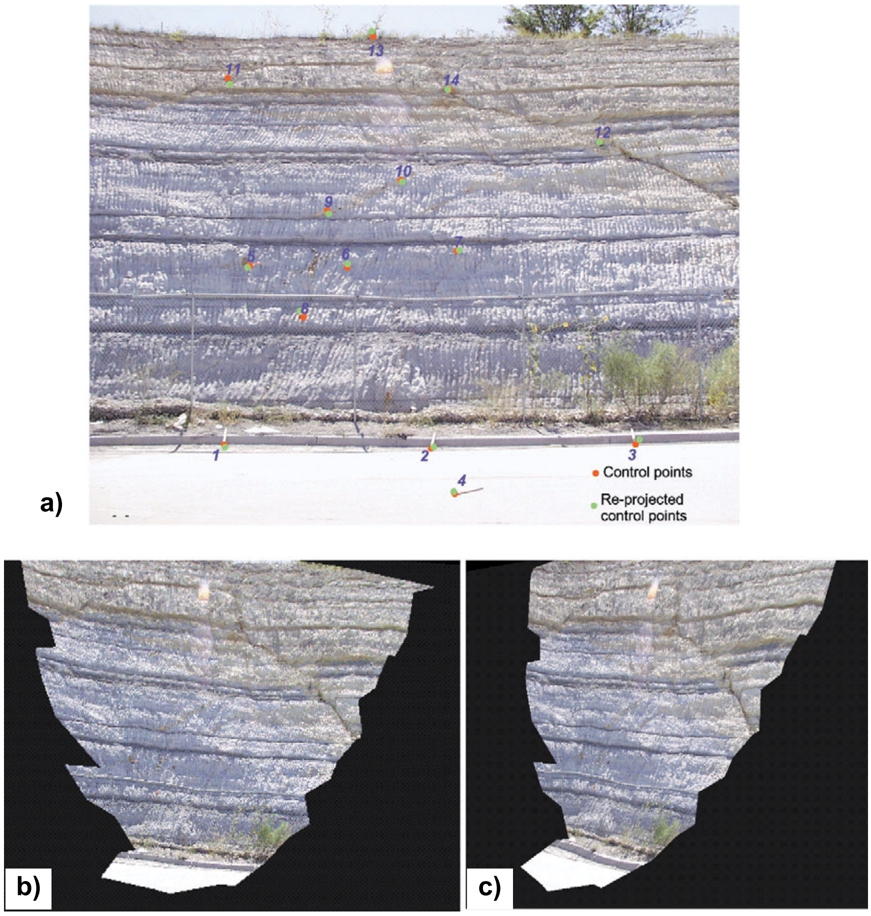

Figure 1. (a) The outcrop photo shows 14 original control points surveyed by reflectorless Topcon total station (red). Using these control points, the camera geometry can be explicitly solved and then the points "back projected" onto the image plane (green). Standard deviation is about 4.2 pixels. (b) and (c) Mapped portion of outcrop from two view angles. The image was draped on the laser mapped terrain surface to produce a photorealistic outcrop.

flight, phase modulation/detection, and geometry. The maximum measurable range and accuracy of a laser range finder depend on target type, size, reflectivity, and atmospheric variables. The accuracy of the range measurement for different kinds of laser range finders can vary from a few millimeters to a few meters, but their ability to measure angles is the greatest limitation on a position (the error increasing with distance). A total station may have a maximum measurable range of 80 m reflectorless to a poorly reflective target (such as terrain) but 10 000 m to a corner reflector prism used in conventional surveying.

On the other hand, reflectorless laser range finders ("guns") have maximum ranges of 500 m or more, with angle errors in decimal degrees and ranges in decimeters. An important feature of some laser range finders is continuous sampling or "trigger on" mode. These laser range finders operate in nanoseconds and provide positions 3-4 times a second. This makes it possible to collect data along a line by sweeping the "laser gun" across an outcrop. The result is a digital "laser sketch" of the geologic feature—typically a contact, boundary or surface, such as a fault trace or the top or base of a bed. This allows rapid mapping without visiting the target.

When this capability is coupled with GPS, local terrain/geologic models can be generated very quickly. When the outcrops can be traced over a distance (particularly across a drainage area, such as on different sides of a valley), solving a "three-point problem" will readily yield strike, dip, and other orientation information, although this often assumes that the surface is planar.

Finally, a detailed digital terrain model provides an elegant, accurate base for outcrop visualization.

Integrating GPS and GIS. Advances in computing allow GPS/laser-positioned data to be stored and used digitally in the field. Small, rugged, pen-based computers can handle large software packages (including GIS) that facilitate data management and generation of digital maps. Physical attributes (e.g., lithology) can be added to any given data point which means that note-taking can be digital as well. The ability to record digitally does not change the basic process of lithologic identification, but it does simplify the process by recording the observation directly "on" the map.

With this in mind, we built our GIS field-mapping software to interface with GPS and various continuous operating laser instruments for geologic mapping and analysis. The system accepts real-time GPS data for positioning laser or total station control points, or directly logging GPS/laser points for topography or geologic features. All data are recorded in ESRI's shapefile format, making it easier to input into GIS packages. The system has many standard GIS capabilities (zoom in/out, panning, and spatial or attribute query) and can perform some geologic analysis such as calculating strike and dip and generating cross-sections even in real time. More importantly, it provides the framework for more sophisticated 3-D modeling and analysis.

The photorealistic outcrop. A photorealistic outcrop is derived through a mapping process that glues the photograph of that outcrop on the terrain surface. A key problem is generation of the texture coordinates for the terrain surfaces. The common approach in GIS and remote sensing is to use a polynomial function to transform the image into world space through the control points. This approach is easy to implement, because it does not require any knowledge of camera geometry. However, it is appropriate only when the perspective is near perpendicular, there is a minimum accuracy requirement, and the relief is

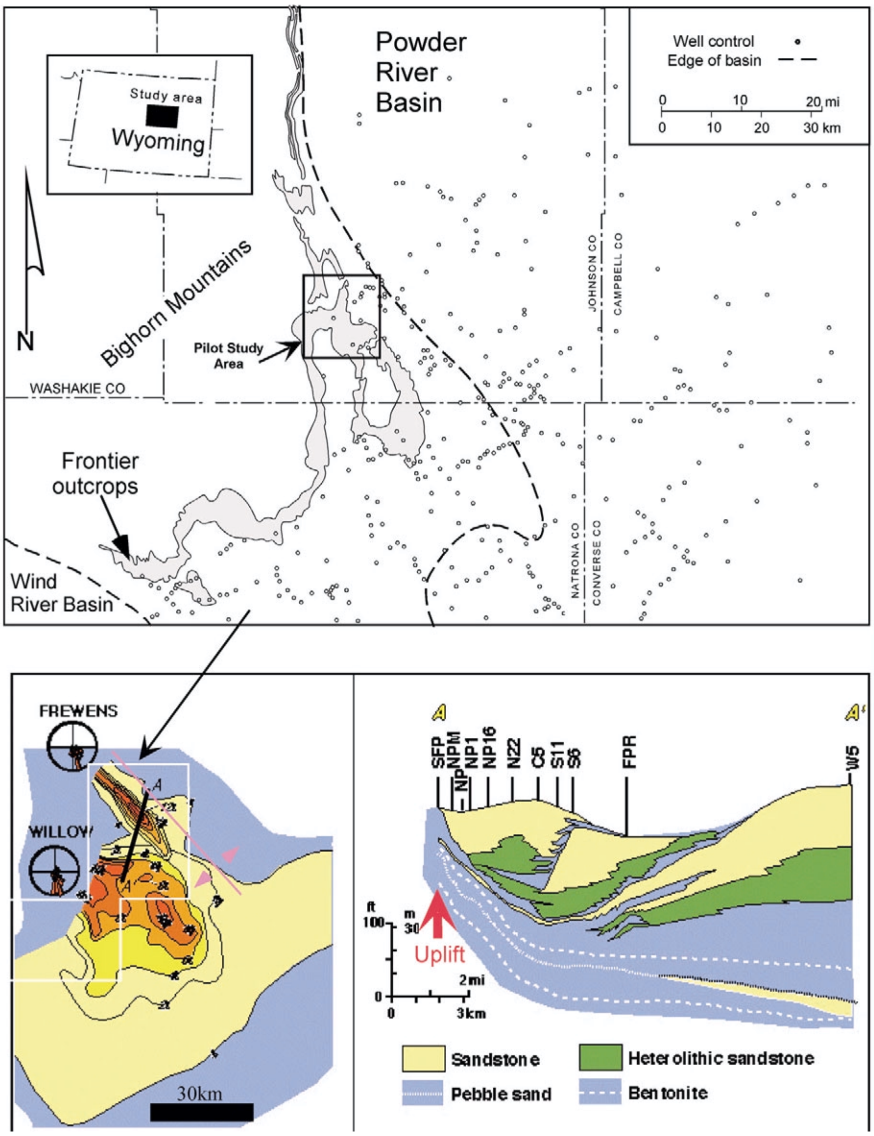

Figure 2. (a) Map of Frontier outcrop belt showing study areas and well-log data. (b) Sandstone isolith map of elongated Frewens delta deposited in a trough created by differential compaction around the Willow delta lobe to the southeast and a structural high to the northeast (after Willis et al., 1999). (c) Cross-section showing the onlap of sandstones against this structural high. Correlation of the bentonites by Bhattacharya and Willis clearly shows the folding.

small, such as in the case of a satellite image or aerial photograph. Outcrop photographs taken in the field are generally highly oblique and subject to radial and tangential camera distortions. Capturing outcrop photographs is actually a process of projecting outcrops into image planes through the camera lens. In order to map the photograph onto the terrain surface in higher resolution, we could model the camera geometry. This includes intrinsic and extrinsic camera parameters and correction of lens distortion.

The approach we used successfully is to rely only on control points to solve camera geometry and lens distortion. We assume that the light rays from the object to its image are collinear. This allows us to determine the camera geometry through linear minimization and nonlinear optimization. Lens distortion can be corrected at the same time. Therefore, a digital image can be tied directly to a terrain model. The result is a three-dimensional photorealistic outcrop.

A photorealistic outcrop was created in the Cretaceous Austin Chalk near Dallas, Texas, U.S. Geologic contacts, faults, topographic random points, and topographic break lines were surveyed through an RTK-controlled total station. The terrain surface was modeled through a constrained triangulation mesh. A picture of the outcrop was taken by a digital camera (resolution = 1280 × 1024 pixels). Fourteen control points were identified on the image (Figure 1a). Camera modeling yields a standard deviation error about 4.2 pixels, which is about 20 cm in accuracy. Figures 1b and 1c show the photorealistic images from two view angles.

Generation of a photorealistic "virtual" outcrop allows a user to "walk through" the virtual outcrop in an immersive virtual environment. The outcrop could then be lifted so the user can display the associated subsurface information. On-screen digitizing on the photorealistic virtual outcrop would provide true three-dimensional coordinates of features, which provides a new way to map more geology.

Examples. Over the last five years, our research group has performed field exercises using various digital-mapping configurations in several scales. After transporting the laser gun/tripod and an RTK GPS receiver/radio to the survey site, it takes about 15 minutes to set up the laser system and position the station and azimuth control. It also typically takes 15 minutes

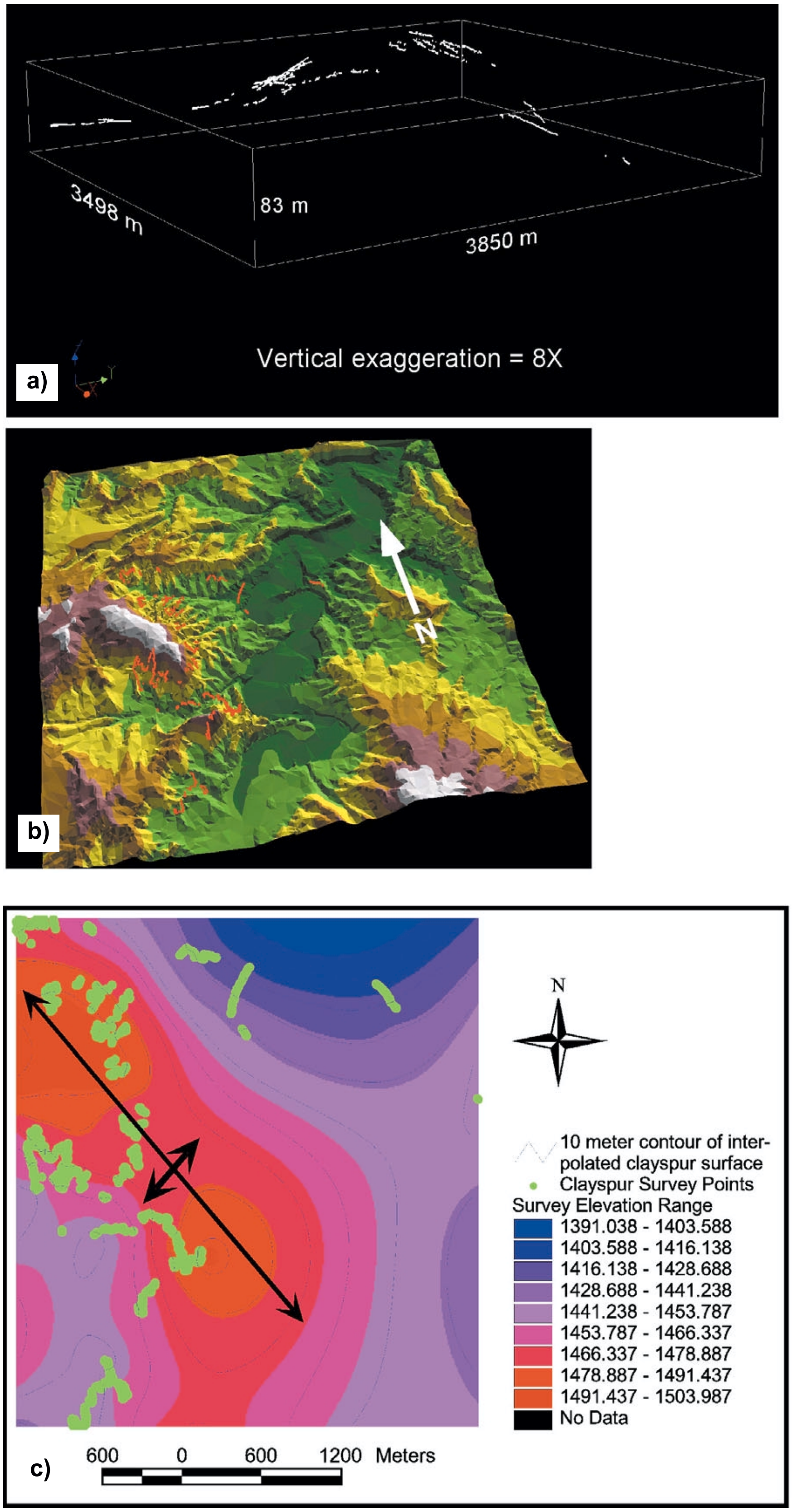

Figure 3. (a) 3-D perspective, mapped using Laser Atlanta range finder system and RTK GPS, shows the present-day folding of the Clayspur bentonite. (b) Terrain map with Clayspur data points overlain (red). See Figure 2a for location. (c) Interpolation of present day Clayspur bentonite surface. The contoured surface shows the northwest-fold axis, also obvious in the perspective view.

to map ("laser sketch") everything (topography and features) visible to 500 m (theoretically) or 400 m (practically), depending on the characteristics of the surface and type of the laser system. The equipment is then moved to the next location in order to continue mapping. We mapped 6-8 contacts over outcrops up to 1 km wide in less than a half an hour in inaccessible vertical cliffs. Data are stored on PCMCIA cards or directly input to a rugged, pen-based computer.

Mapping subtle regional structures in Wyoming. This study investigated the relationship between deposition of ancient delta lobes that formed around subtle syntectonic structures within the Cretaceous Frontier Formation in Wyoming's Powder River Basin (Figure 2a). The deltas had been mapped in detail in a previous allostratigraphic study that focused on the internal geometry of beds within the mapped deltas (Figures 2b and 2c). This new study focused on the larger scale tectonic features (tens of meters in amplitude) that control the position of the delta sandstone bodies. These types of structures may relate to changes in tectonic intraplate stresses and may be an important factor in creating subtle unconformities in the stratigraphic record, as well as controlling the position of reservoir sandstone bodies in hydrocarbon reservoirs. Conventional mapping, using topographic maps and air photos, usually allows determination of 3-D position to about 5-10 m. This is acceptable for determining the x,y position but is totally inadequate for determining elevation of low-amplitude structural features. GPS/laser data resolve this difficulty via rapid measurements with accuracy in x,y,z of centimeters to decimeters in seconds. Consequently, it is possible to map subtle variations in the elevations of beds that relate to the long wavelength, low-amplitude structures.

This study demonstrated the logistics, methodology, and timetable for collecting data over 40 km^2 in detail and coarsely over 150 km^2. Personnel became familiar with the outcrop locations and the detailed allostratigraphy mapped earlier during three days of training. An RTK GPS receiver and radio was established on a high topographic point, which allowed accuracy of a few centimeters for positions

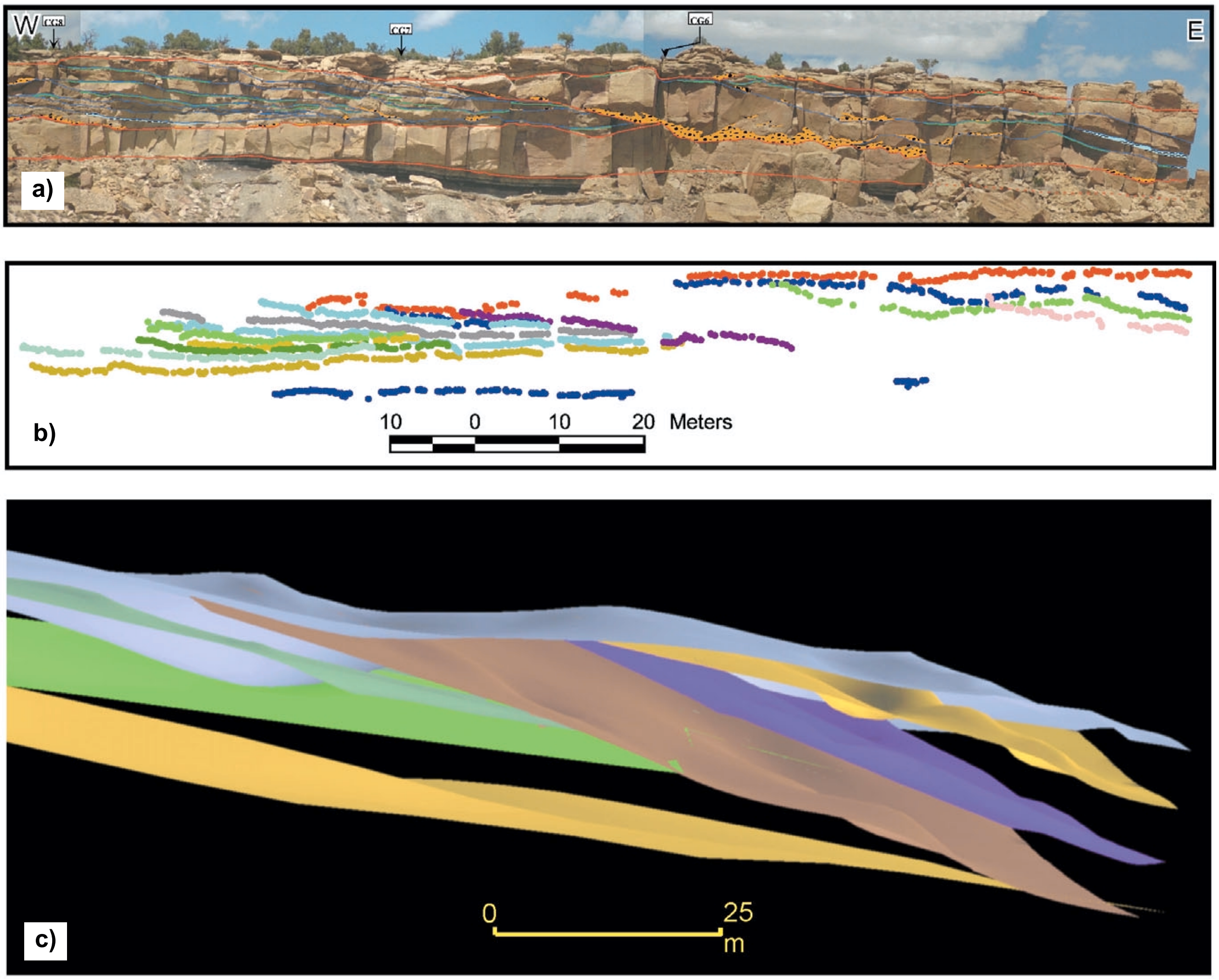

Figure 4. (a) Photo mosaic of Corbula Gulch outcrop, looking northeast, showing sedimentological bounding surfaces, and location of measured stratigraphic sections. A large delta plain channel containing inclined bedding cuts into the east side of the outcrop. (b) Data points of the bounding surfaces shown in Figure 4a mapped with a Laser Atlanta range finder. Individual points are in 3-D UTM coordinates. The points were projected onto an x-z plane in order to compare visually with the outcrop photo. (c) 3-D perspective of various bounding surfaces, fitted to the laser mapping and corehole data points and interpolated across the conjoining cliff faces. These surfaces will be used to develop a quantitative volume for reservoir flow-simulation studies.

within a 10-km radius in real time. The bentonite beds to be mapped are extraordinarily visible as white layers and other beds such as pebble and massive sandstone beds are identifiable because of their association with these. Most contacts of interest are distinctive even at several hundred meters, especially when seen through the telescopes of the laser system. Sites from which important features and surfaces were visible were picked and then positioned by RTK GPS before tracing by laser gun.

Figure 3a is an example. The base bentonite layer is the Clayspur and the geographic distribution of the outcrop of that layer and the character of the surrounding terrain (Figure 3b) indicates just how effective this method is. A 3-D distribution of the mapped Clayspur and a surface fit (Figure 3c) displays the present structure.

3-D reservoir characterization of outcrop analogs in Utah. A second study mapped internal structure of dipping beds that formed as a result of accretion of sandy bars in an ancient river. These river channel deposits occur within the Cretaceous Ferron sandstone in Central Utah. The study was geared toward developing detailed 3-D models of channelized facies elements for reservoir/aquifer characterization and fluid-flow modeling. GPS and laser systems were used for two different aspects of the study: (1) to locate 2-D and 3-D GPR surveys, coreholes, outcrop measured sections, and mapping of beds in the outcrop (Corbula Gulch outcrop), and (2) to map thin mudstone beds that drape the bars in an area with adjacent vertical cliffs in different orientations. Because the same beds could be mapped around an outcrop bend, we were able to interpolate the 3-D geometry. Surface and subsurface data were integrated and visualized at Corbula Gulch. Tops and bottoms of sandstone layers, mapped along the outcrop (Figures 4a and 4b) and defined by core drilling, were positioned by GPS and then fitted to surfaces and visualized (Figure 4c). This 3-D rendering can now be used as the basis for a 3-D gridded volume for flow simulation. The GPR survey data also provide independent determination of the 3-D facies architecture of these systems. The purpose of the second study, mapping synsedimentary growth faults at Muddy Creek, was to provide a 3-D rendering of a structurally and stratigraphically complex area and to test GPS mapping over an area intermediate in scale between Corbula Gulch and Wyoming. During two half days of digital mapping, we generated more than 60 000 data points (Figure 5), including local terrain, major bounding surfaces, and faults. The terrain and sedimentary bounding surfaces were fitted and visualized (Figure 6).

Conclusions. We have developed special software and modified available hardware to create an integrated tool for collecting and positioning digital geologic data in 3-D space. The digital capture of data allows geologic features and maps to be quickly produced in 3-D.

These are useful for understanding

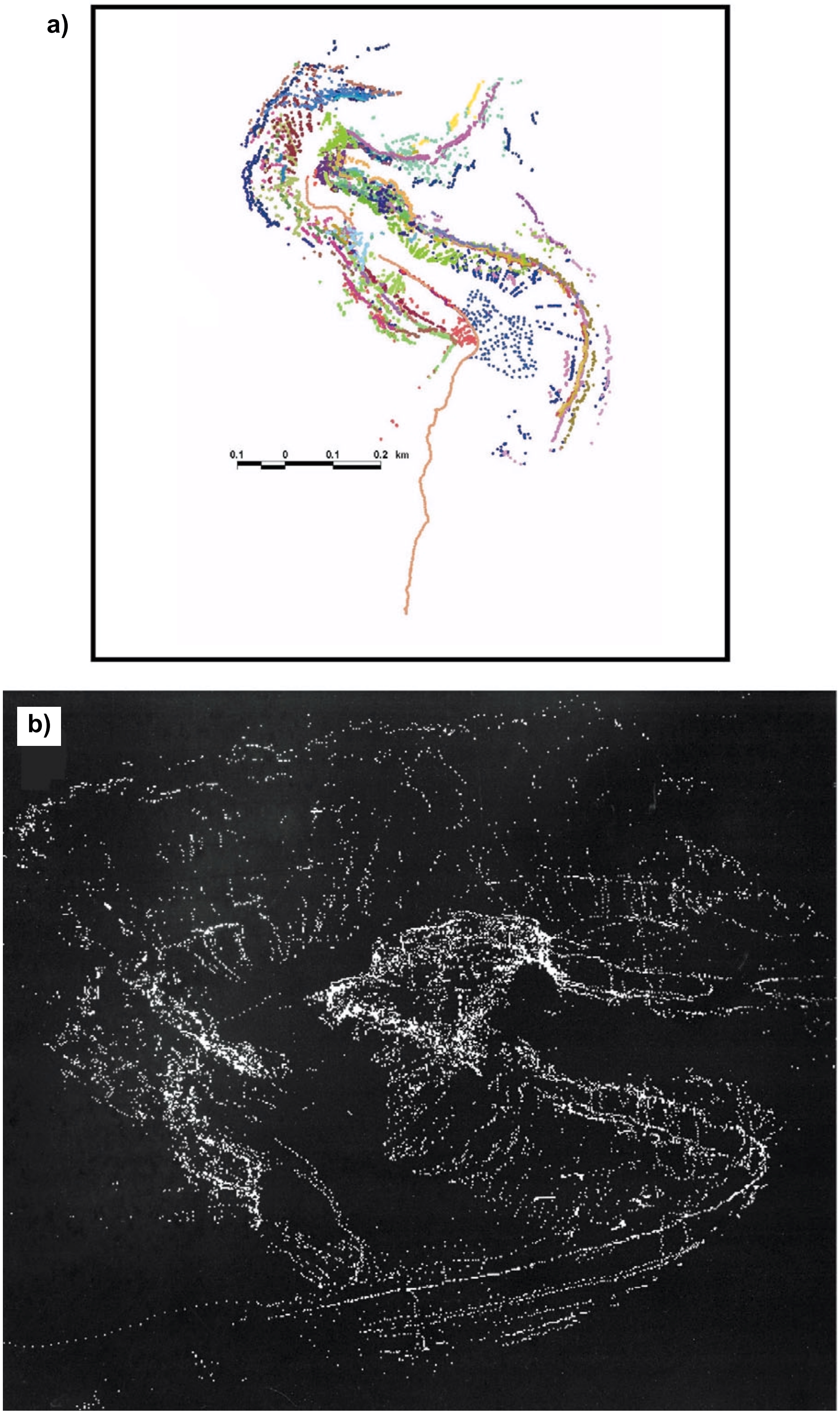

Figure 5. (a) 2-D map of surveyed points by GPS and Laser Atlanta range finder at Muddy Creek, different features coded by different colors. (b) 3-D perspective of surveyed points, looking north. Note the bounding surface line.

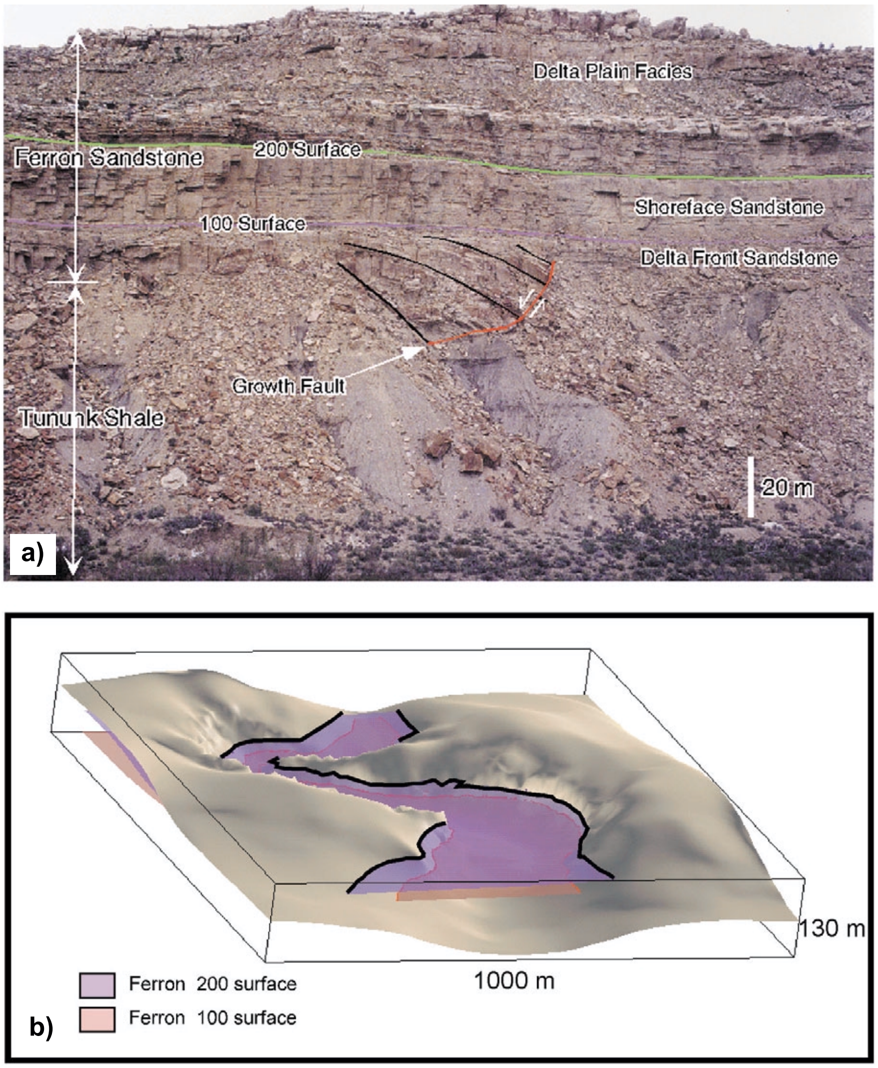

Figure 6. (a) Photo mosaic of Ferron outcrops in Muddy Creek. Note large growth fault in the middle of the photo overlain by flat undeformed strata. Growth faulted strata are restricted to the sands immediately overlying the Tununk shales. Location in perspective to left. (b) Key stratigraphic surfaces (100 and 200 in Figure 6a) were mapped along the walls of Muddy Creek Canyon using the reflectorless laser range finder. Using this data, surfaces were fitted to these data allowing them to be interpolated across the canyon and visually rendered in 3-D. This perspective view shows these interpolated surfaces. Growth faulted strata lie below surface 100.

geologic systems from a variety of perspectives and as input for problems that require 3-D information such as reservoir and aquifer models.

Suggestions for further reading. "Real time and the virtual outcrop improve geological field mapping" by Xu et al. (*EOS*, 1999). *Digital Mapping Methods: Accurate Digital Data Capture and Analysis for the Field Geoscientist* by Nielsen et al. (GSA Continuing Education Manual, 1999). *Digital Photogrammetry: An Addendum to the Manual of Photogrammetry* (American Society for Photogrammetry and Remote Sensing, 1996). "Architecture of a tide-influenced delta in the Frontier Formation of Central Wyoming, USA" by Willis et al. (*Sedimentology*, 1999) "Lowstand deltas in the Frontier Formation, Wyoming, U.S.A. by Bhattacharya and Willis (in press AAPG *Bulletin*).

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